Coronagraph Science & Requirements

(focusing on small-medium missions)

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Heritage of Recent Thought

- TPF-C STDT
  - extensive, well thought out requirements to discover & characterize terrestrial planets in habitable zone
  - presumes large aperture, many $B
- Multiple small coronagraph proposals
  - EPIC, TOPS, PECO, ECLIPSE.....
  - less well developed, proposal quality science cases
  - in depth studies now in progress
- ExoPTF
  - focus on big picture strategy, ordering of missions
  - ultimate goal of habitable planet characterization

Full Disclosure

ExoPTF Report: "While our Task Force fully appreciates the great scientific potential for characterizing extrasolar giant planets from space, we recognize that this capability may not lie on the critical path to directly detecting and characterizing extrasolar terrestrial planets. **Any mission that will accomplish our primary goal will (if properly defined) also characterize numerous giant planets.** We thus do not call specifically for a cool giant planet characterization mission. However if technological innovation enables an inexpensive new approach, or if a mission specifically designed to detect such planets turns out to lie on the critical path to characterization of Earths, we would enthusiastically await its discoveries."

Today

- Classes of targets
  - ground vs. space
- Goals of characterization
- Impacts on requirements

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Philosophy: want more than pale blue dot image

Classes of Targets

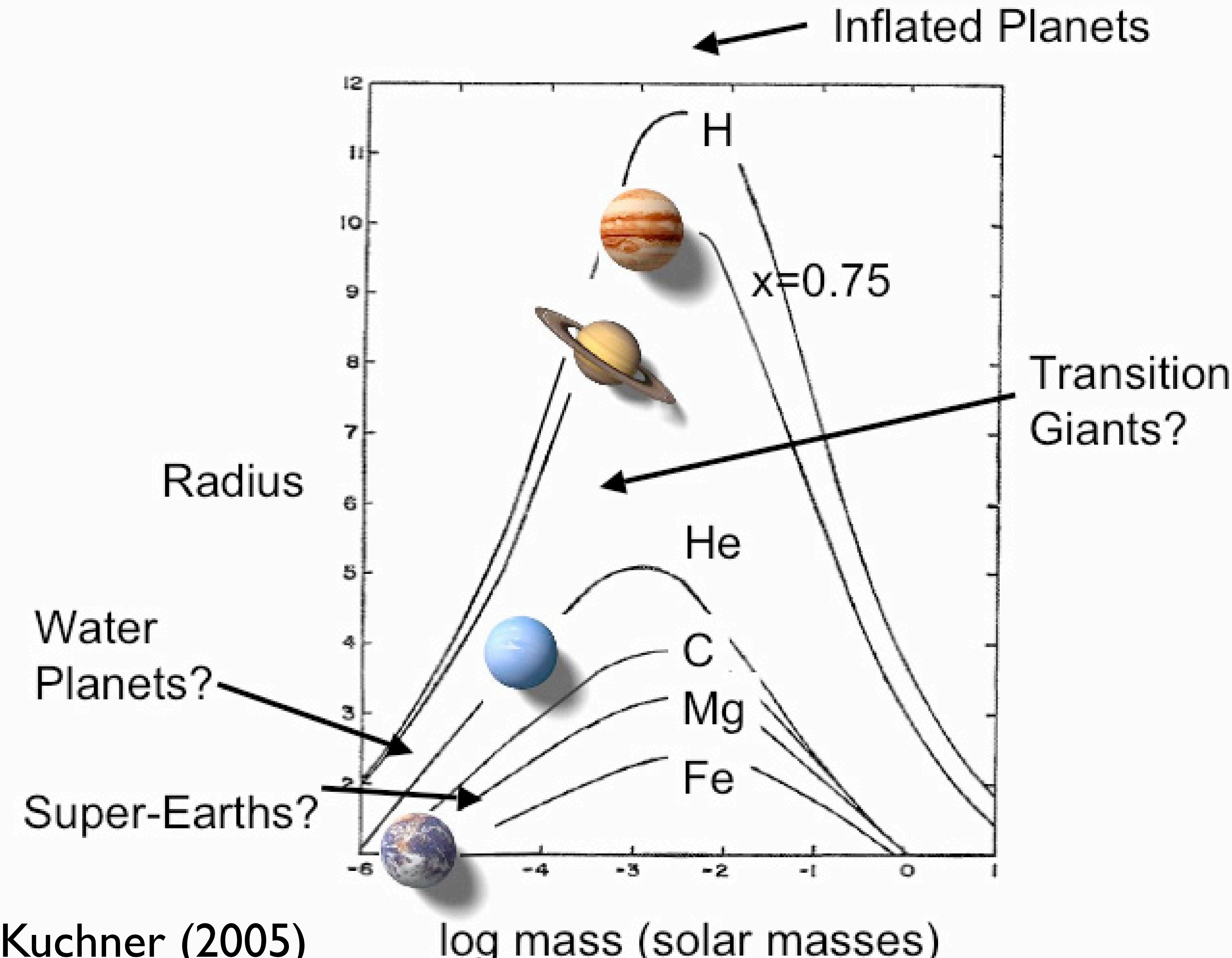
- Giants
  - gas - Jupiter
  - “ice” - Neptune
  - transition to brown dwarfs - 55 Cnc d
- Terrestrial Planets
  - expect great diversity
  - Super Earths, water worlds, etc.

Characterization

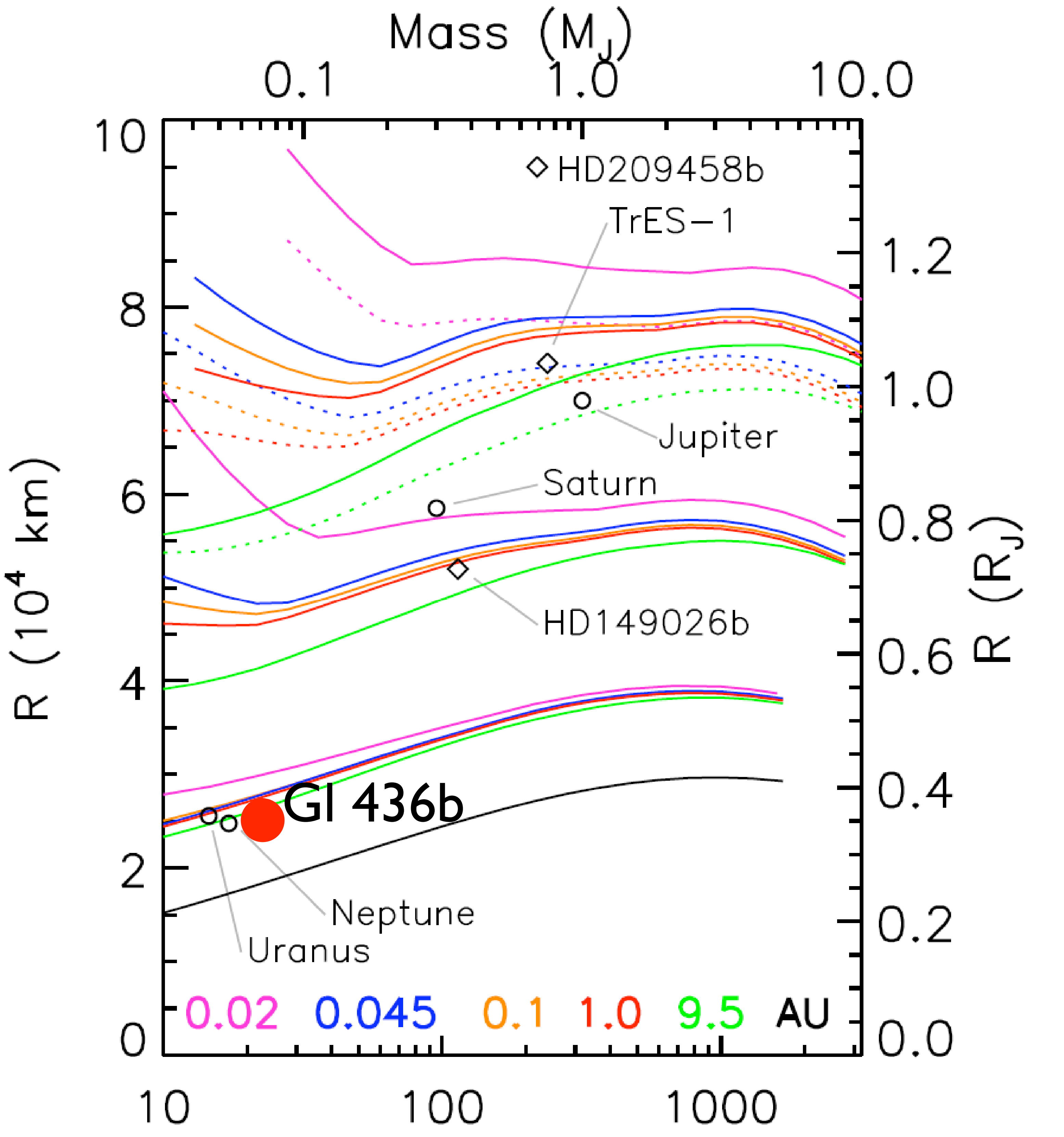
- Mass
- Radius

Mass is Everything (but not the only thing)

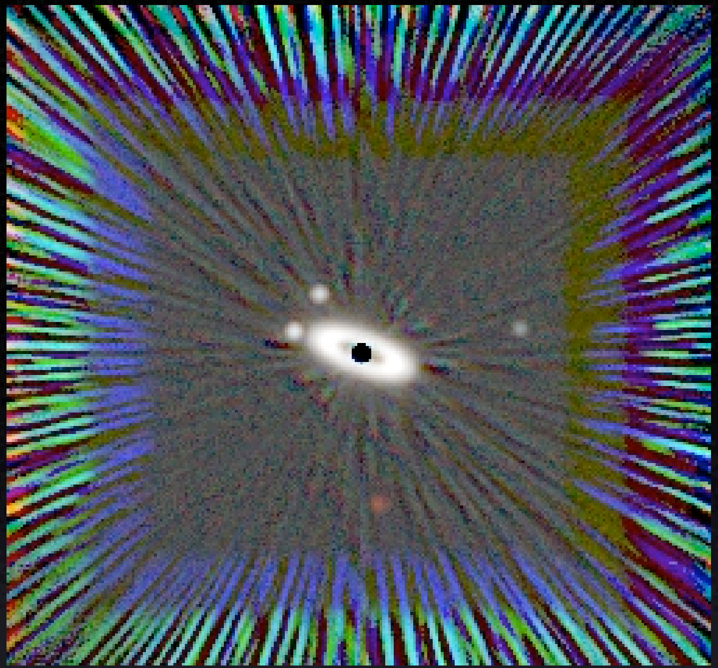
- Interpretation of an object hinges on its mass & radius
  - bulk composition
  - atmospheric scale height, interpretation of spectra
  - atmospheric escape
  - orbital dynamics
- Without mass you only have a dot



Kuchner (2005)



Fortney et al. (2007)



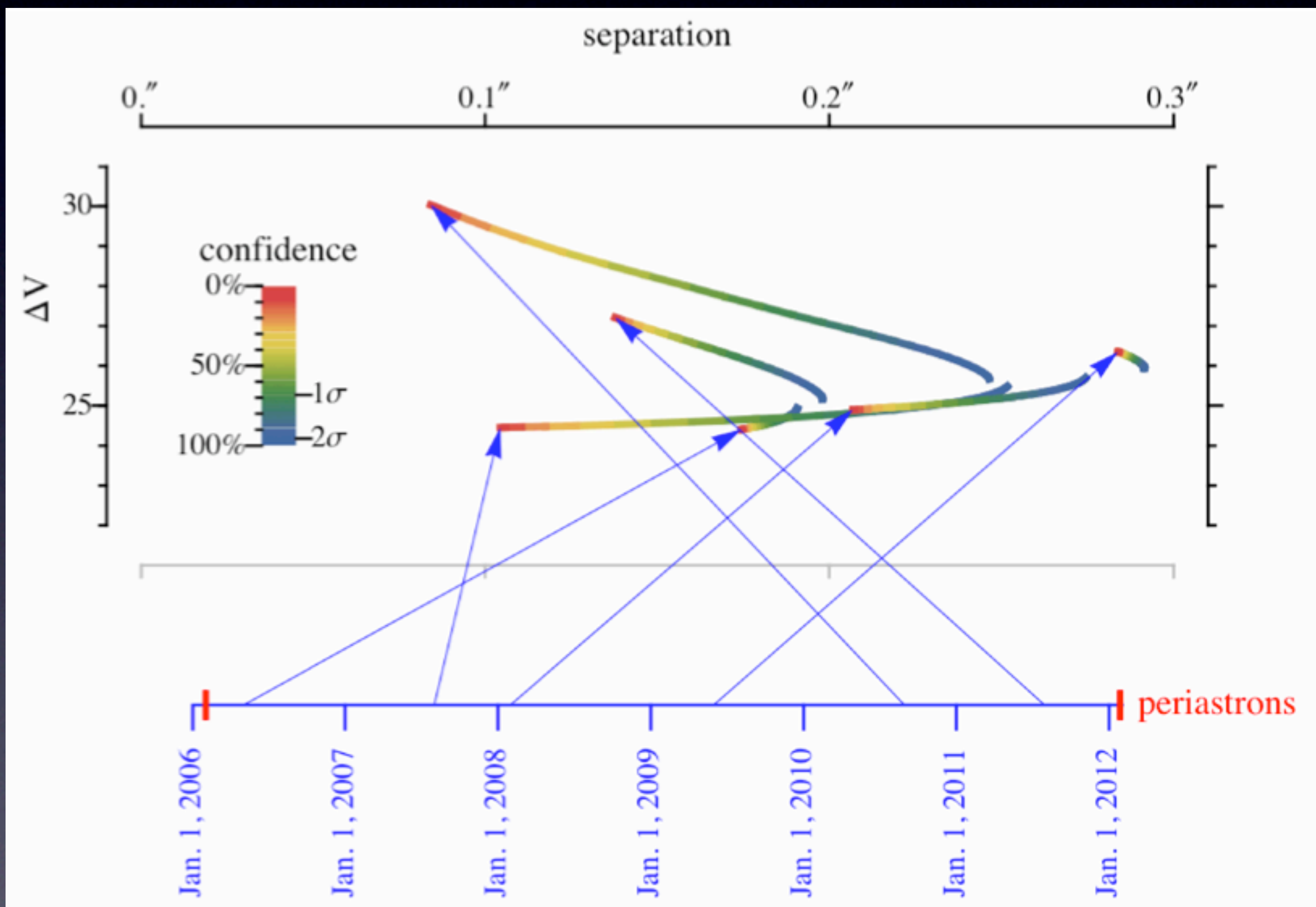
Scattered light alone does not tightly constrain radius or mass since albedo uncertain - R^2a

a may vary by >3x, 70% uncertainty on radius, mass essentially unconstrained

Finding Mass

- Photometric estimates unreliable
  - clouds, photochemistry, surface composition, more variety than we can anticipate
- Spectral gravity indicators plausible, but
  - model dependent, radius, mass, composition degeneracies
  - challenging at low S/N, low R
- Need RV and/or astrometric detection for true characterization
  - 2 images yield mass for RV planets (astrometry constraint in the dark hole relative to unseen star)
  - need to model accuracy given realistic mission
  - fiducial objects allow characterization of other worlds

Detectability of RV Planets



Example of 47 UMa c;
Bob Brown

30% of RV planets are detectable with 2.4 m telescope with coronagraph working at 2λ/D

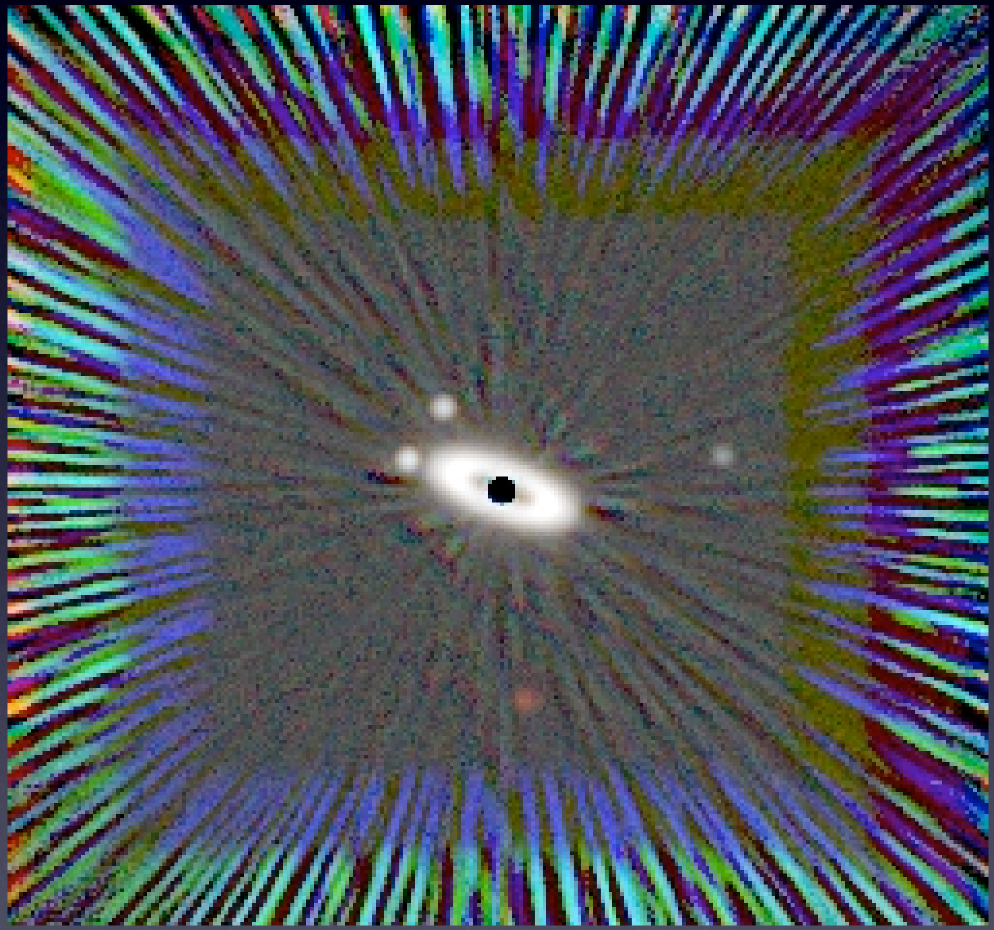
~5% at 1.4m

+ future long period planets

Giants

Beyond Mass

- Long Term
  - Orbit - dynamics, system architecture
  - Phase function - atmosphere, Bond albedo, rings
- Single Observation
  - Composition, Clouds, Temperature



Not all Jupiters are “Jupiter”

Color and albedo are functions of type and depth of clouds.

Clouds depend on BOTH internal heat flow (mass, age) and incident flux.

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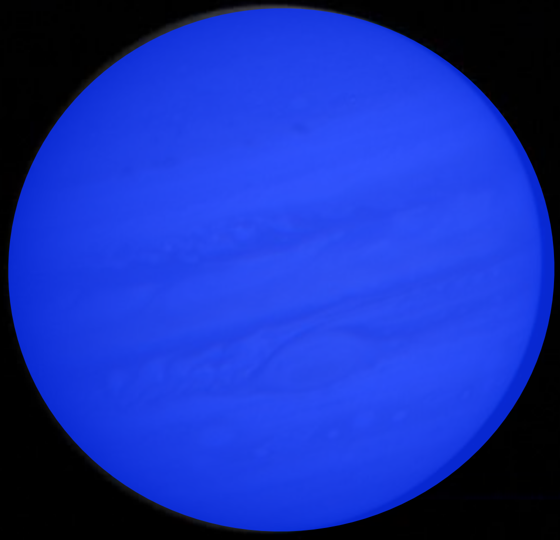

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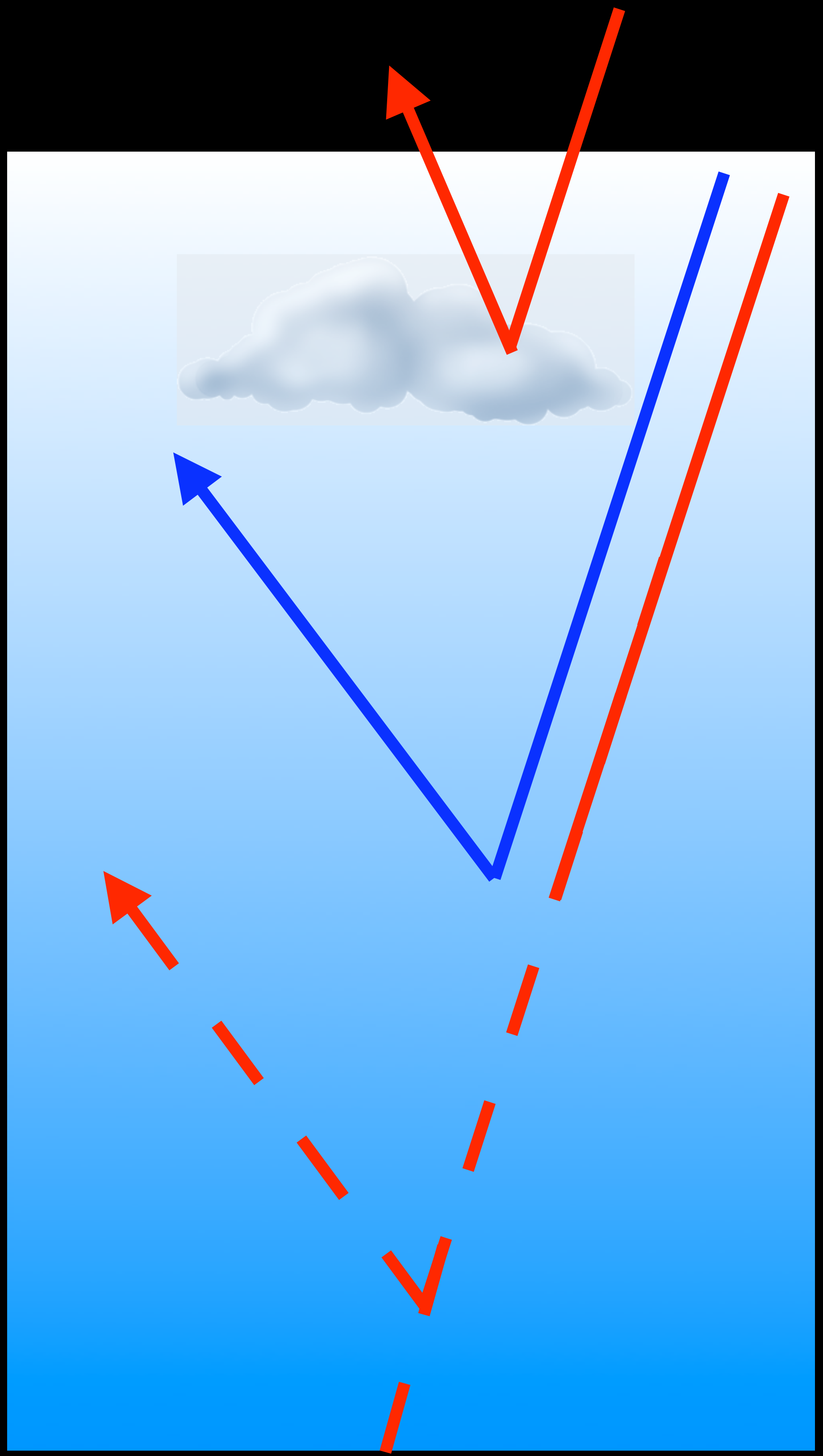
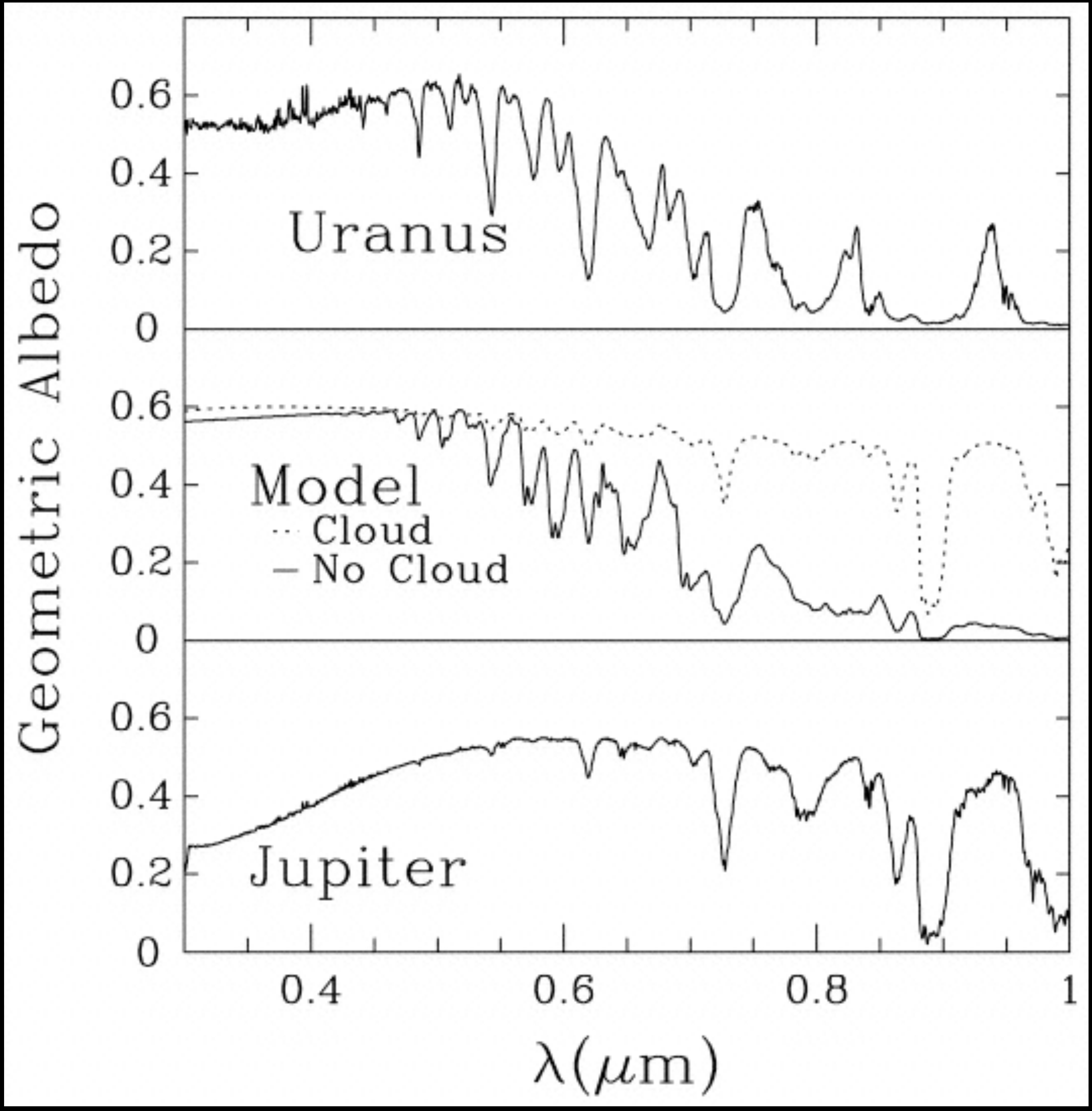
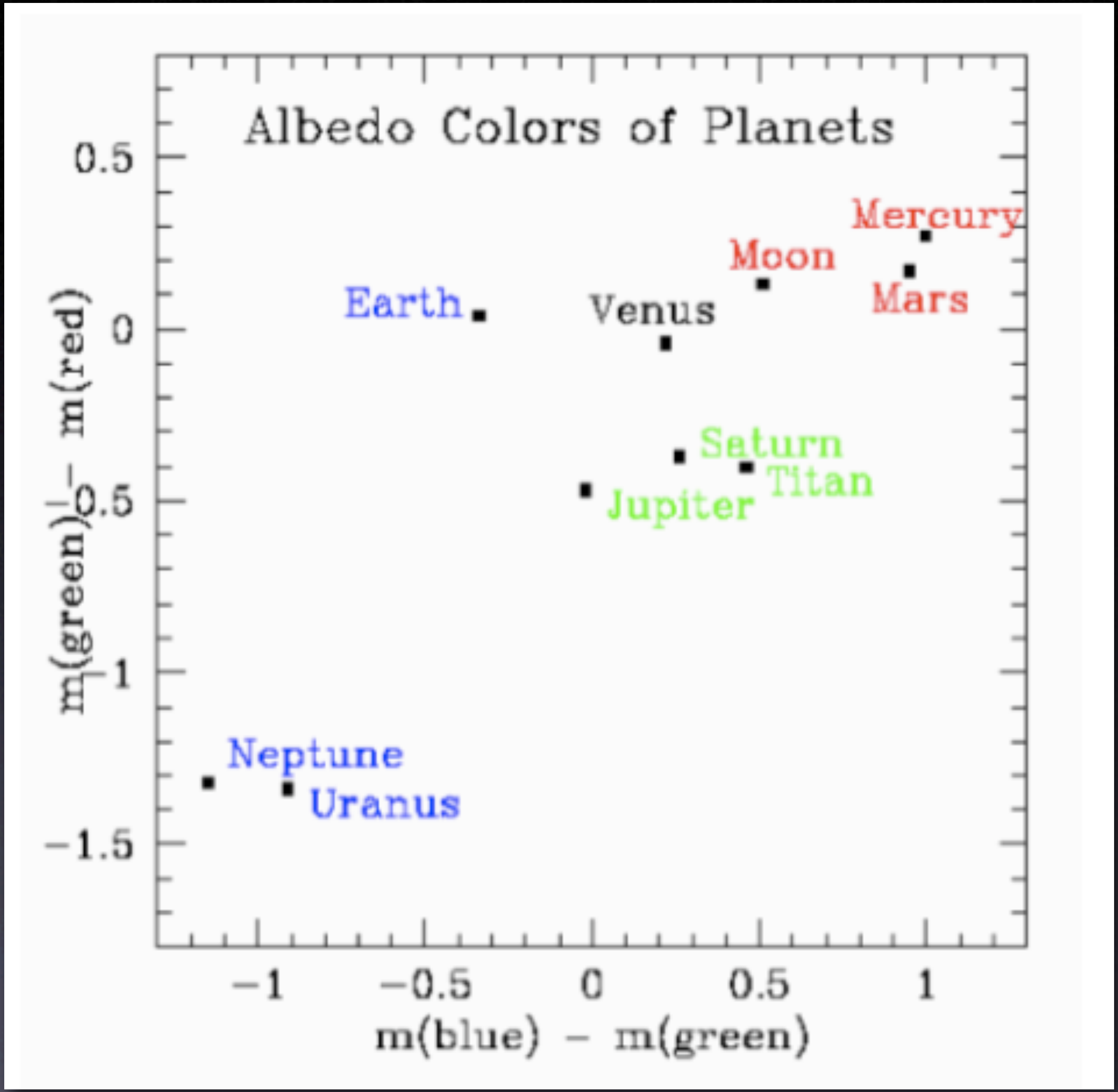
photochemistry

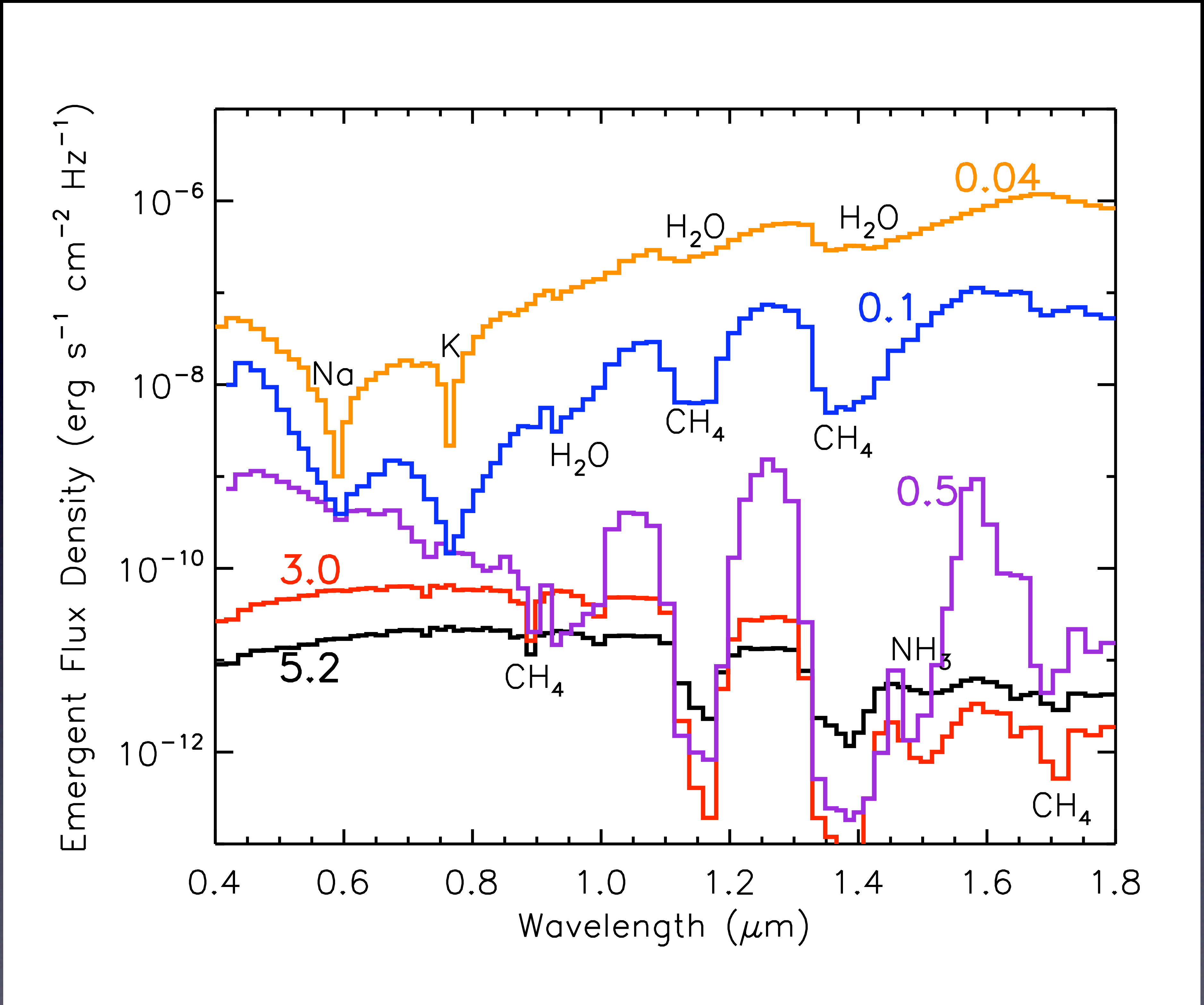




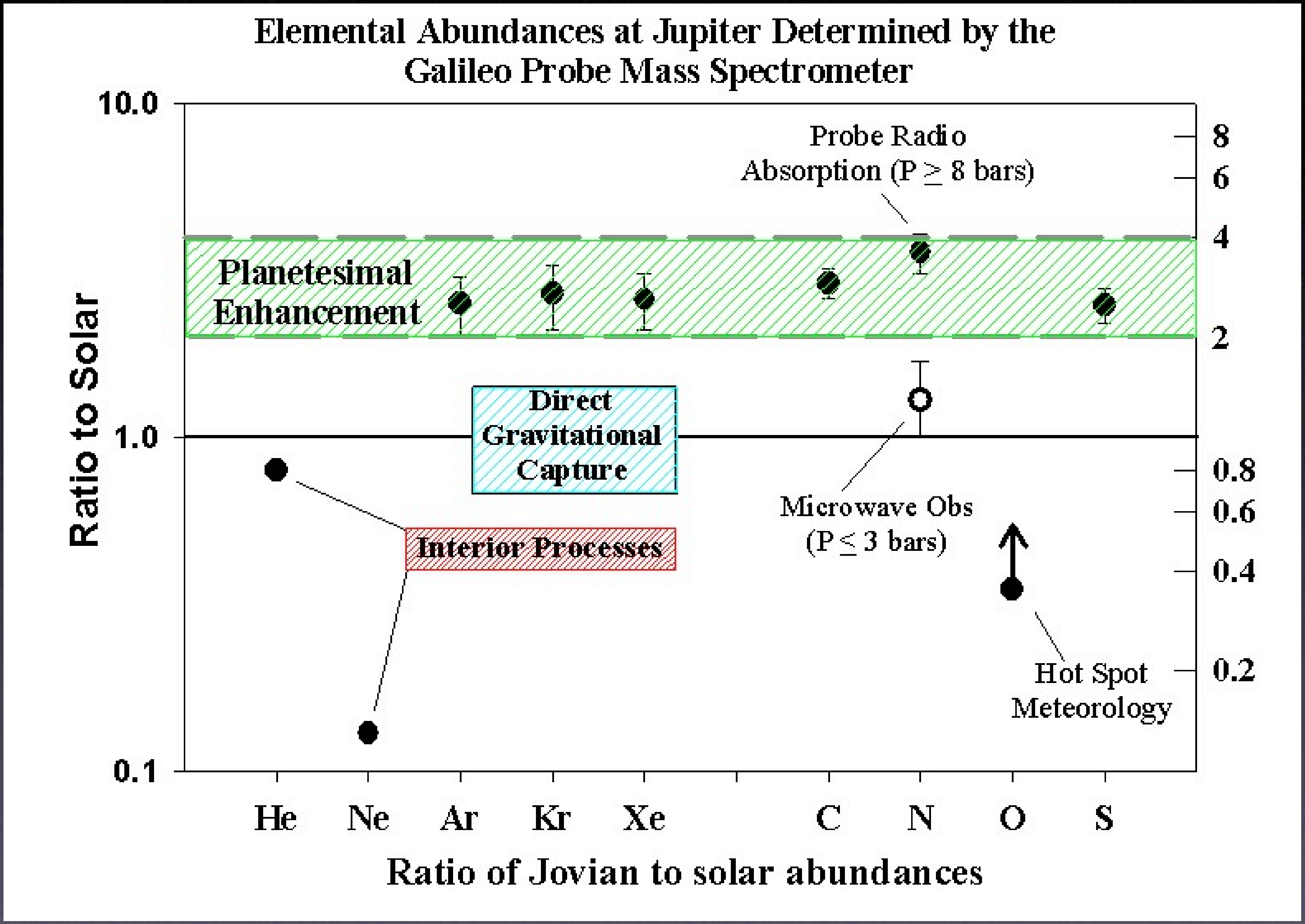
Marley et al. (1999)



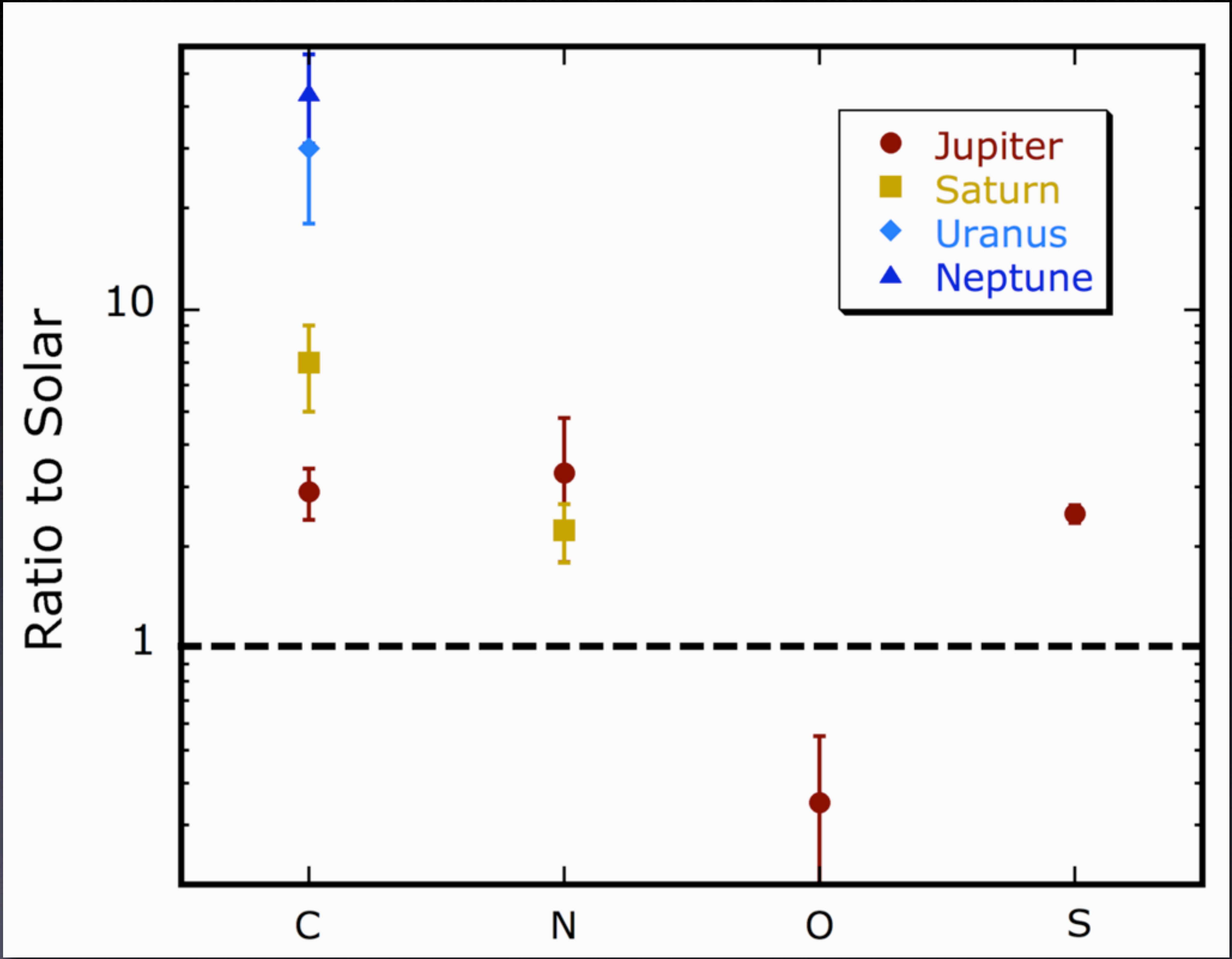
Colors alone are not sufficient for characterization.

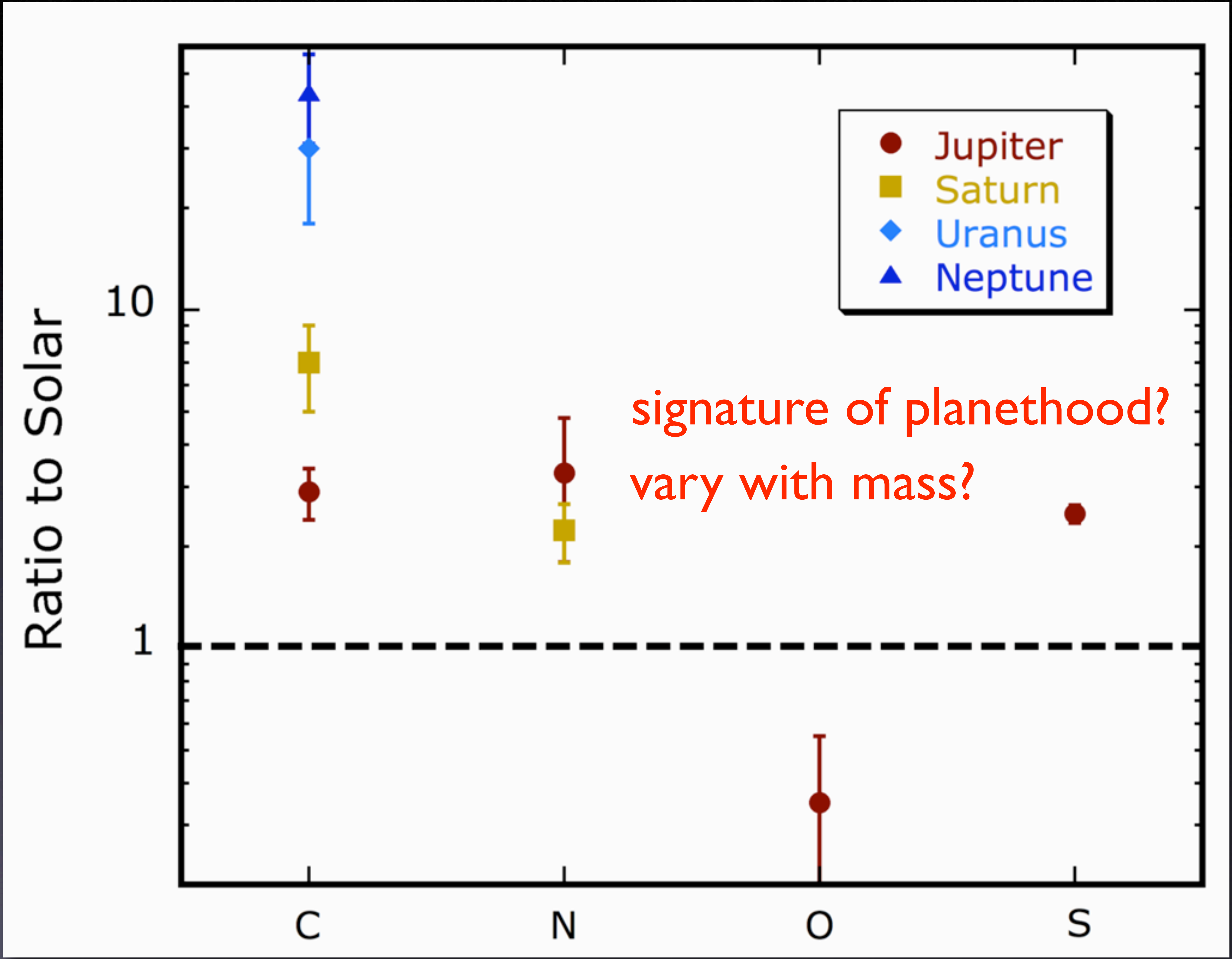


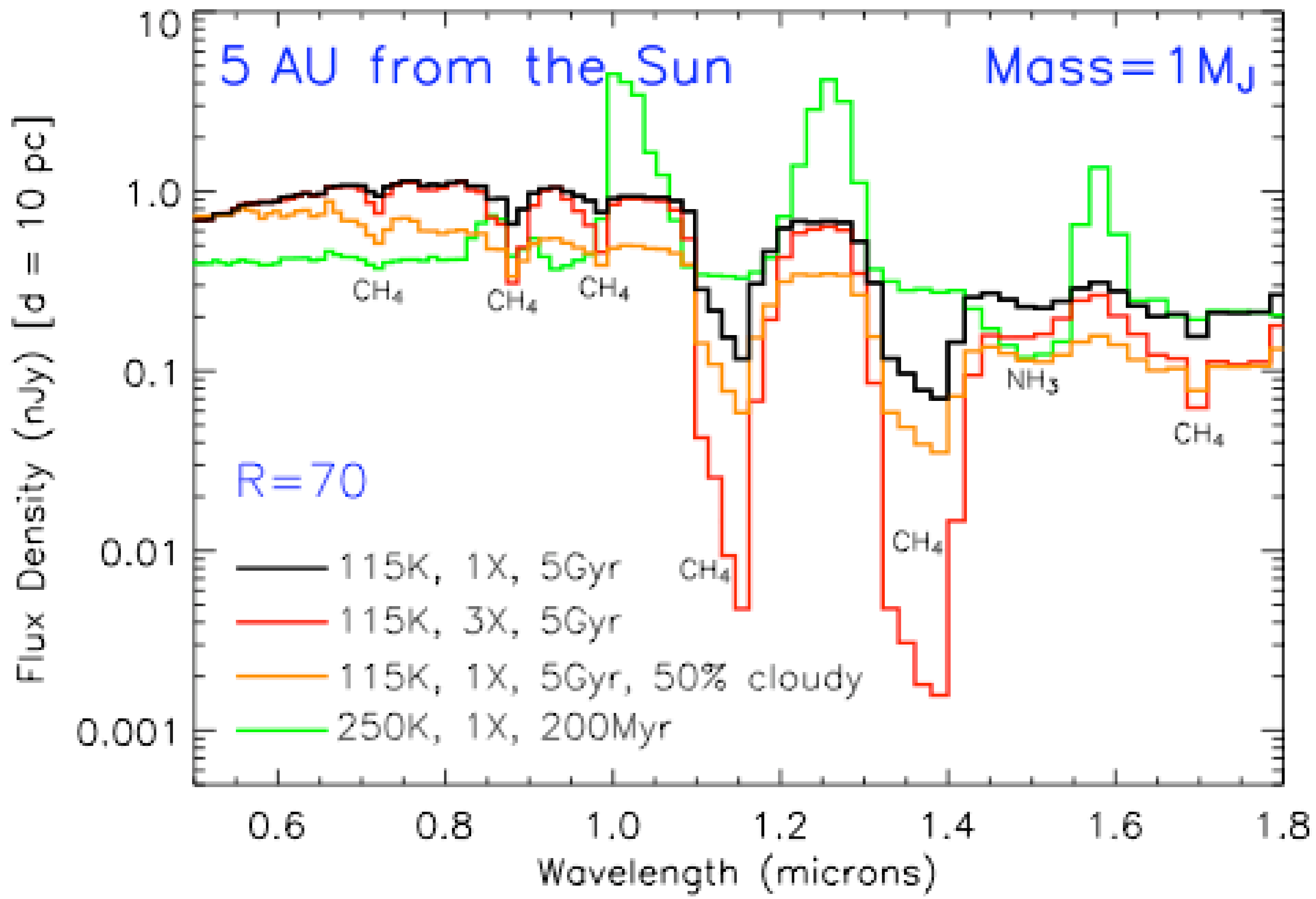
- Spectral shape - continuum/band contrast - yields temperature range
- Constrains gravity and albedo



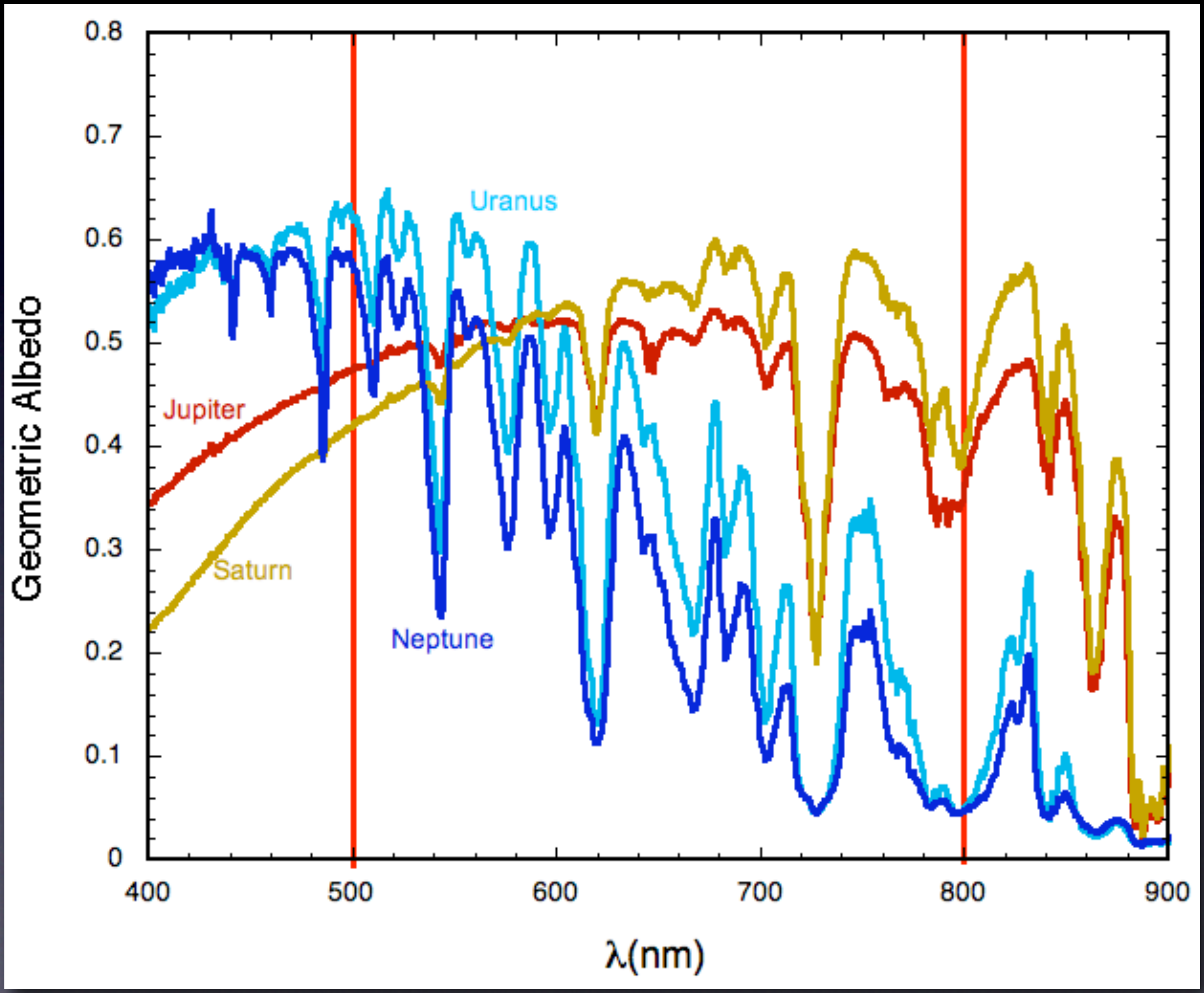
Owen et al. (1999)


Ratio to Solar
10
1
C
N
O
S
Jupiter
Saturn
Uranus
Neptune


Jupiter
Saturn
Uranus
Neptune
signature of planethood?
vary with mass?
Ratio to Solar
10
1
C
N
O
S

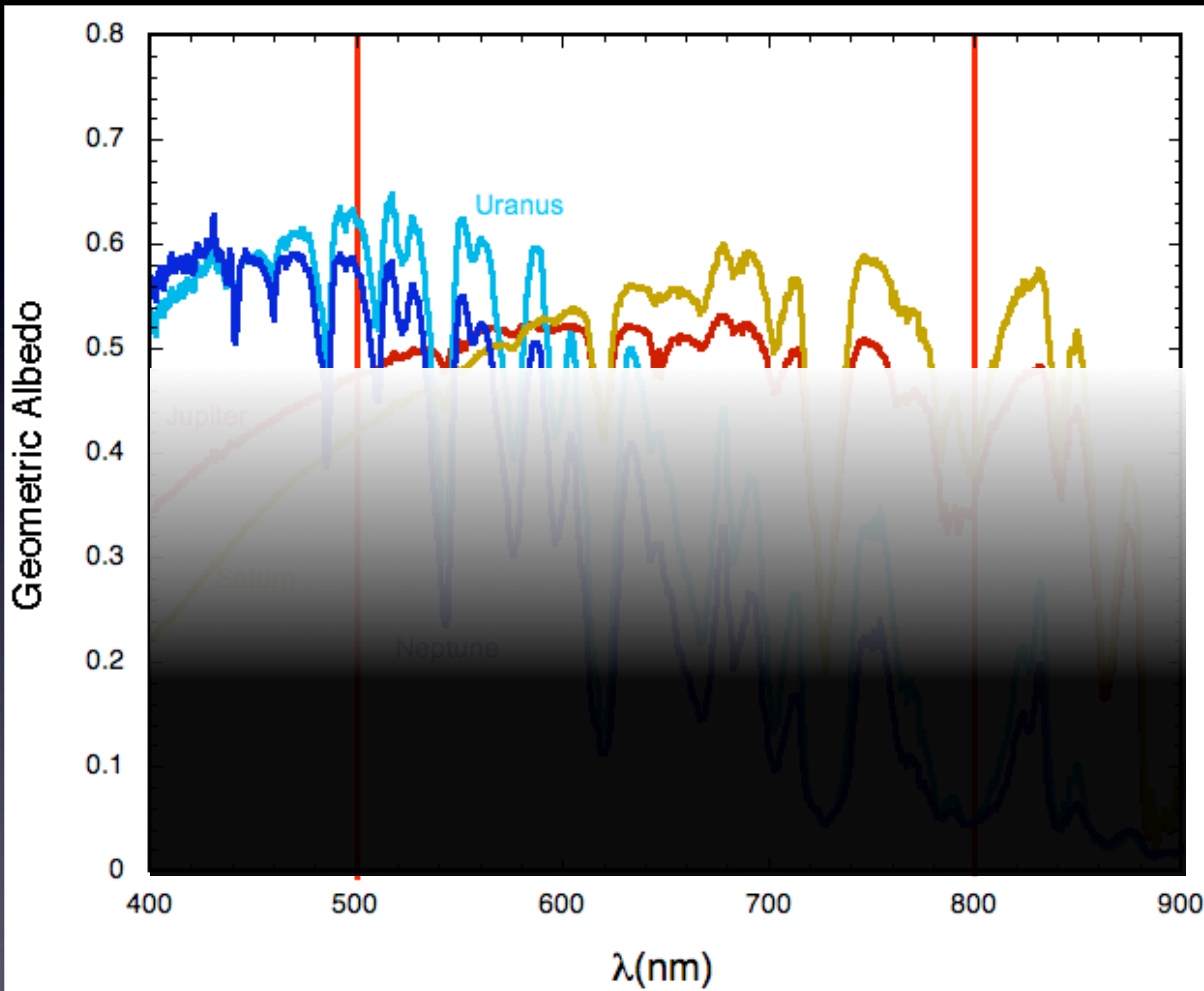

5 AU from the Sun
Mass=1M$_J$
R=70
CH$_4$
CH$_4$
CH$_4$
CH$_4$
CH$_4$
NH$_3$
CH$_4$
115K, 1X, 5Gyr
115K, 3X, 5Gyr
115K, 1X, 5Gyr, 50% cloudy
250K, 1X, 200Myr
Flux Density (nJy) [d = 10 pc]
Wavelength (microns)
10
1.0
0.1
0.01
0.001
0.6
0.8
1.0
1.2
1.4
1.6
1.8

Continuum Alone is not Enough



- Information is in the band depths
- Just detecting continuum with dropouts limits interpretation
- characterization completeness

Continuum Alone is not Enough



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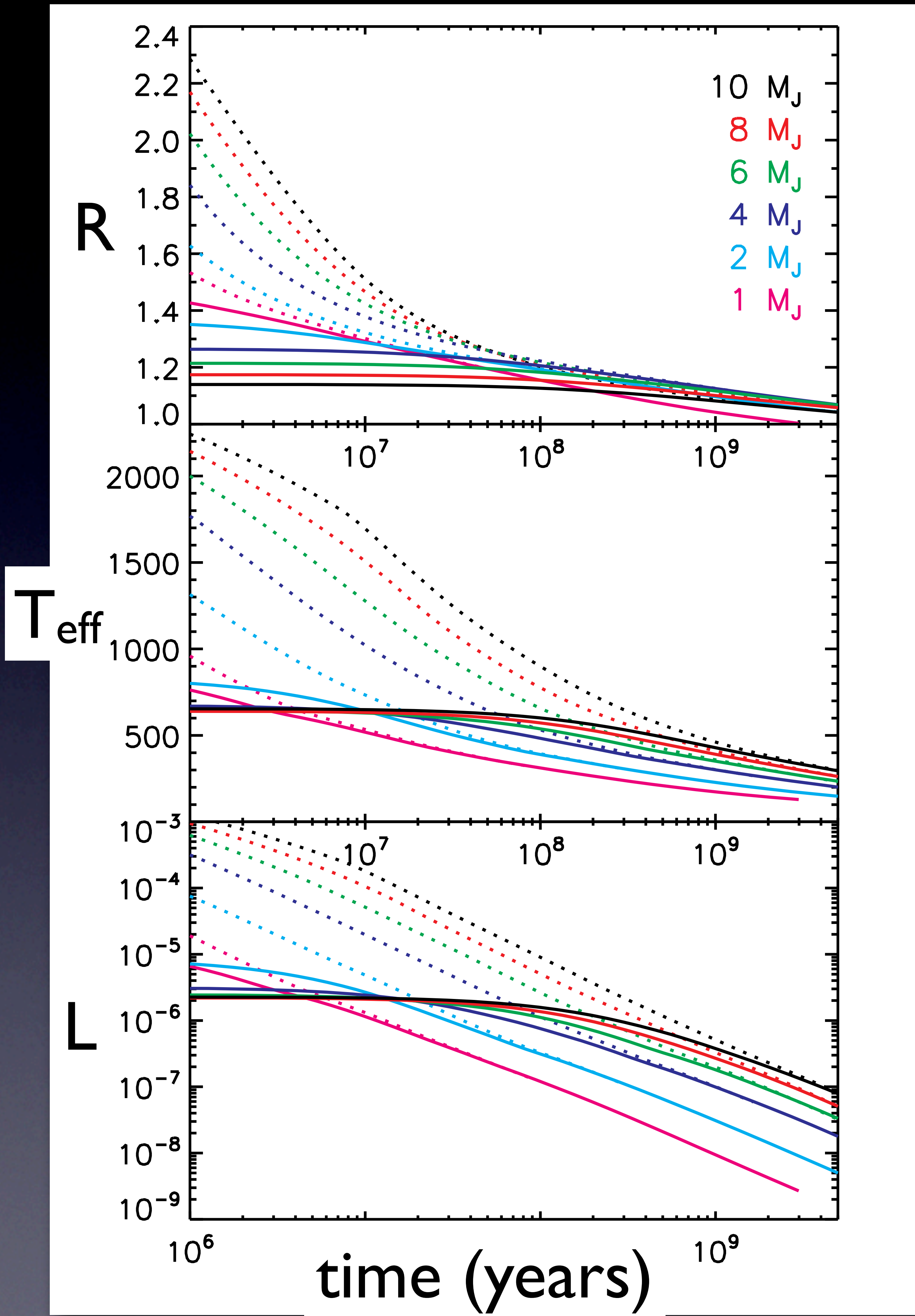
What About the Ground?

Core Accreted Planets:

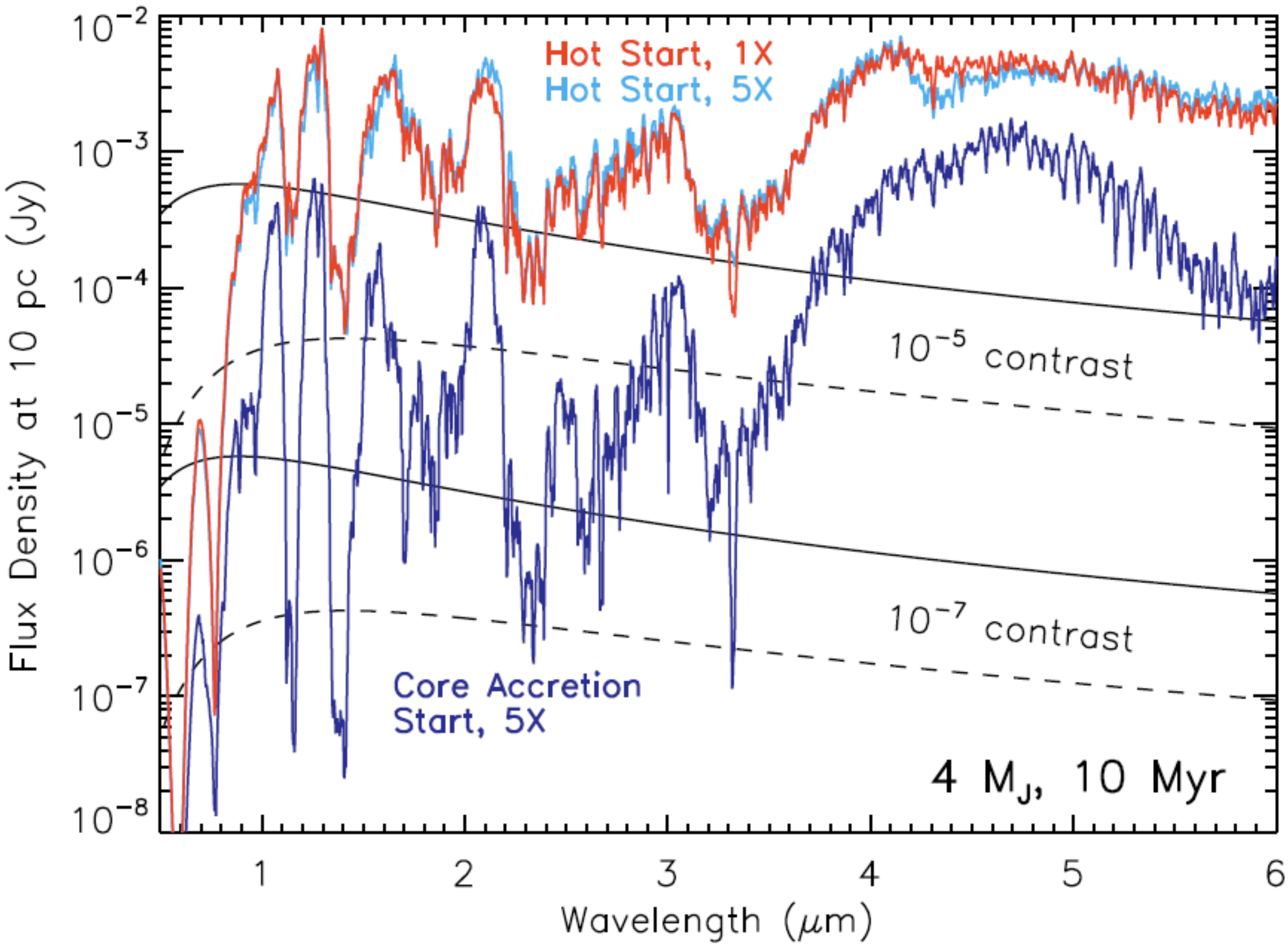


Smaller

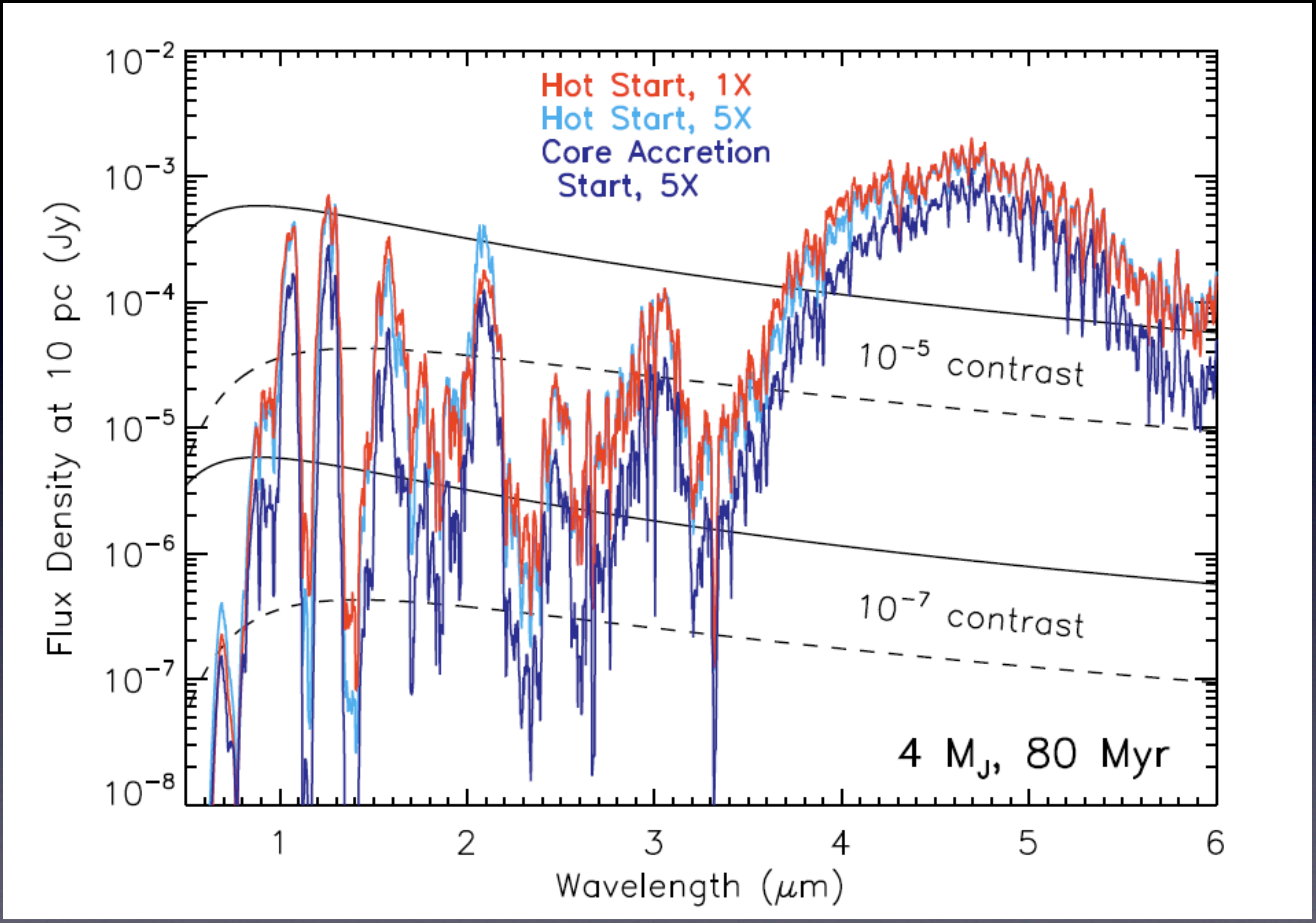
Cooler

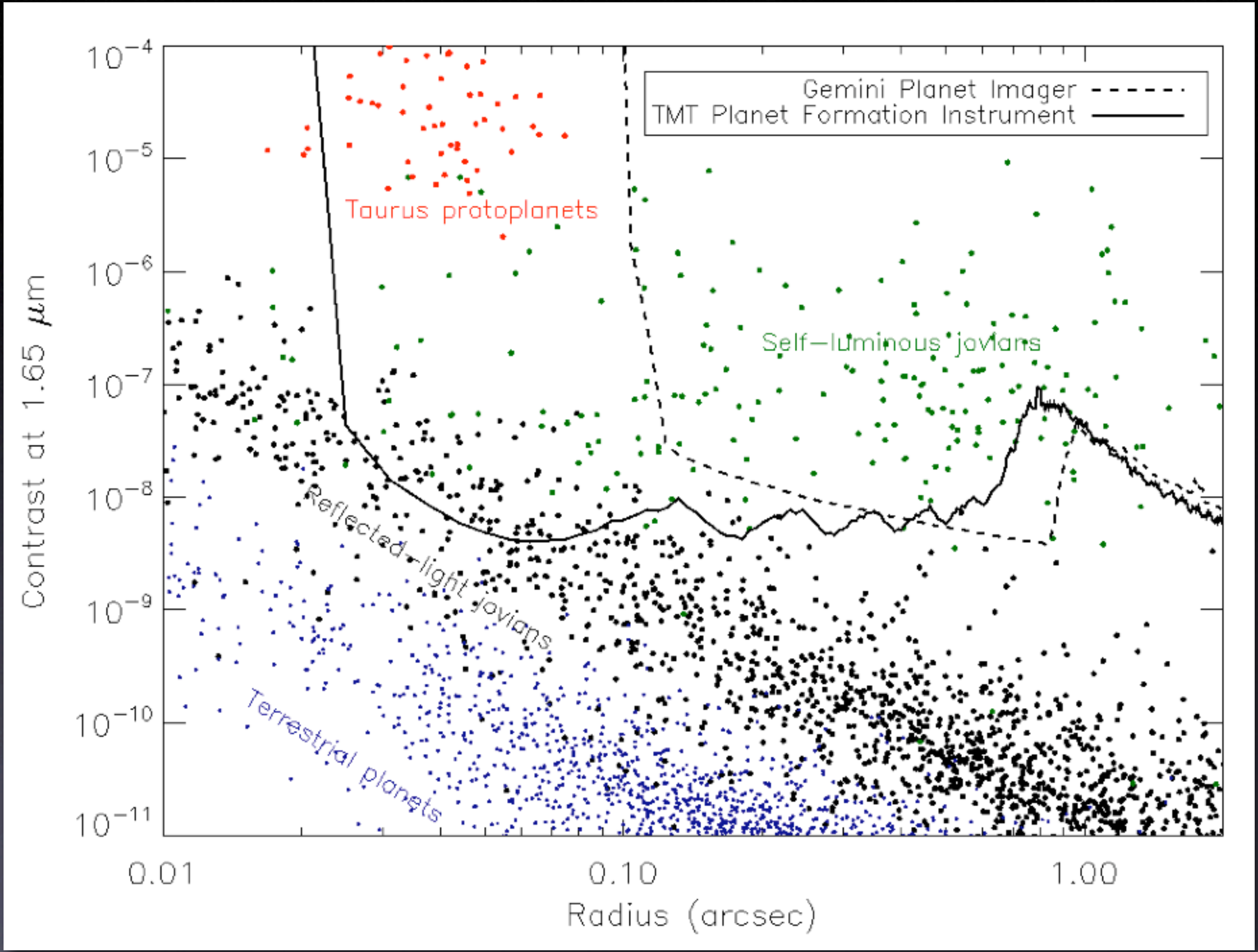
Fainter

Marley et al. (2007)

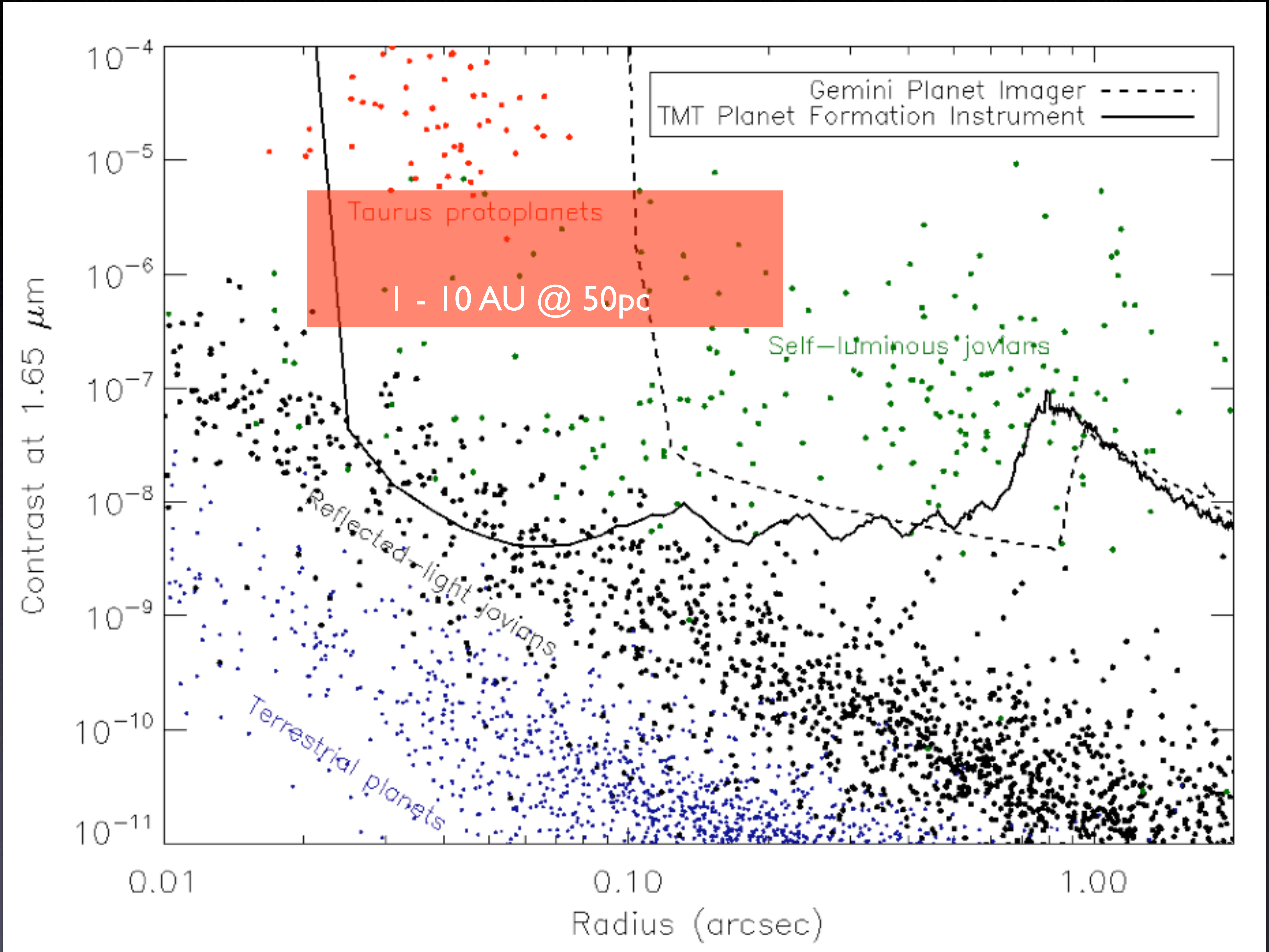


Hot Start, 1X
Hot Start, 5X
10^{-5} contrast
10^{-7} contrast
Core Accretion
Start, 5X
4 M_J, 10 Myr
Flux Density at 10 pc (Jy)
Wavelength (μm)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1
2
3
4
5
6


Hot Start, 1X
Hot Start, 5X
Core Accretion
Start, 5X
10^{-5} contrast
10^{-7} contrast
4 M_J, 80 Myr
Flux Density at 10 pc (Jy)
Wavelength (μm)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1
2
3
4
5
6



Gemini Planet Imager
TMT Planet Formation Instrument
Taurus protoplanets
Self-luminous jovians
Reflected-light jovians
Terrestrial planets
Contrast at 1.65 μm
Radius (arcsec)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.01
0.10
1.00



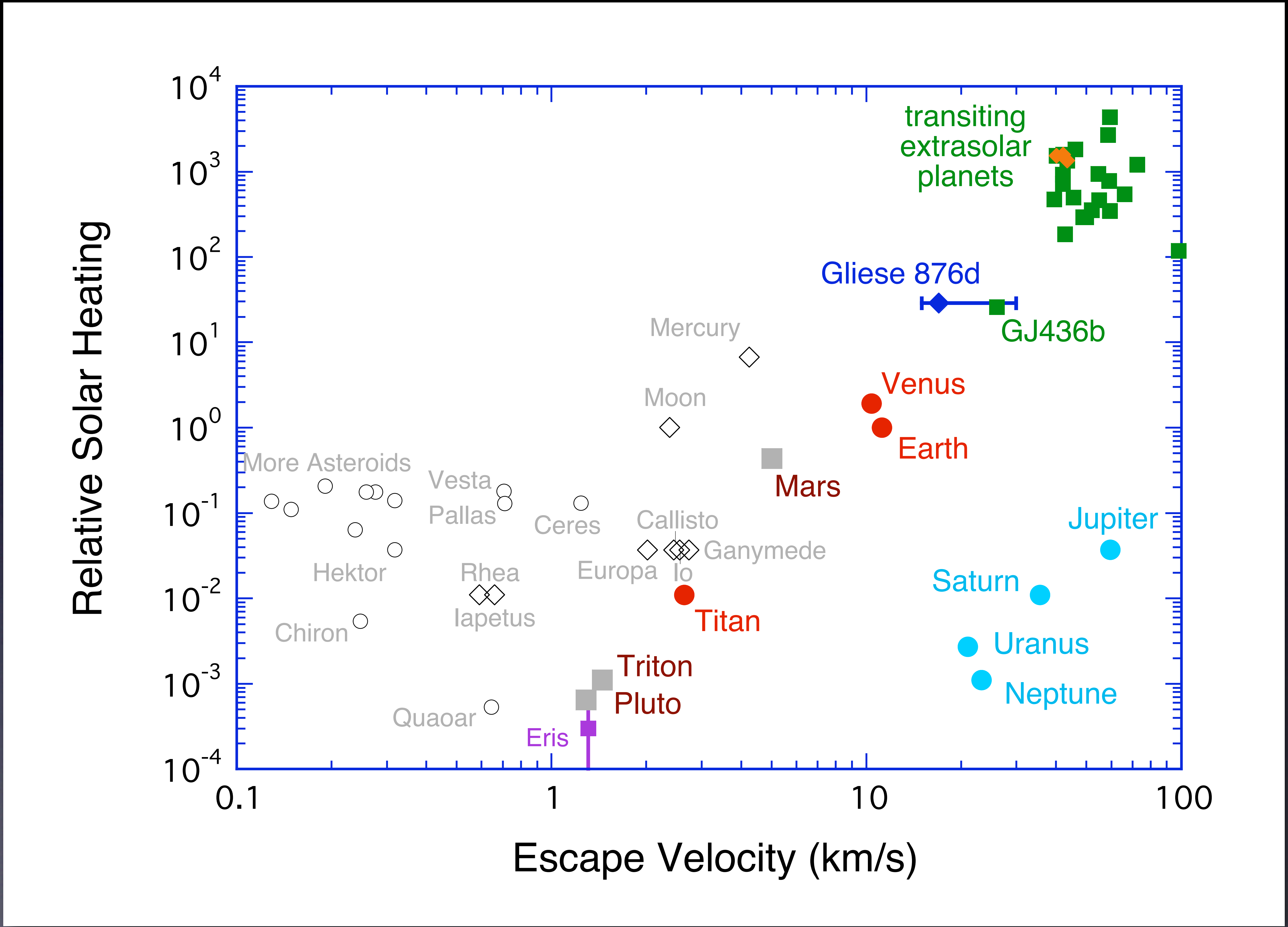
Gemini Planet Imager
TMT Planet Formation Instrument
Taurus protoplanets
1 - 10 AU @ 50pc
Self-luminous jovians
Reflected-light jovians
Terrestrial planets
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Contrast at 1.65 μm
0.01
0.10
1.00
Radius (arcsec)

Jovians from the Ground

- Generally outer reaches of stellar systems
- Detect Jupiters down to ~1 M_J
- Probe formation mechanism
- Composition
- No model-independent mass
- Cannot connect giants to terrestrial planets

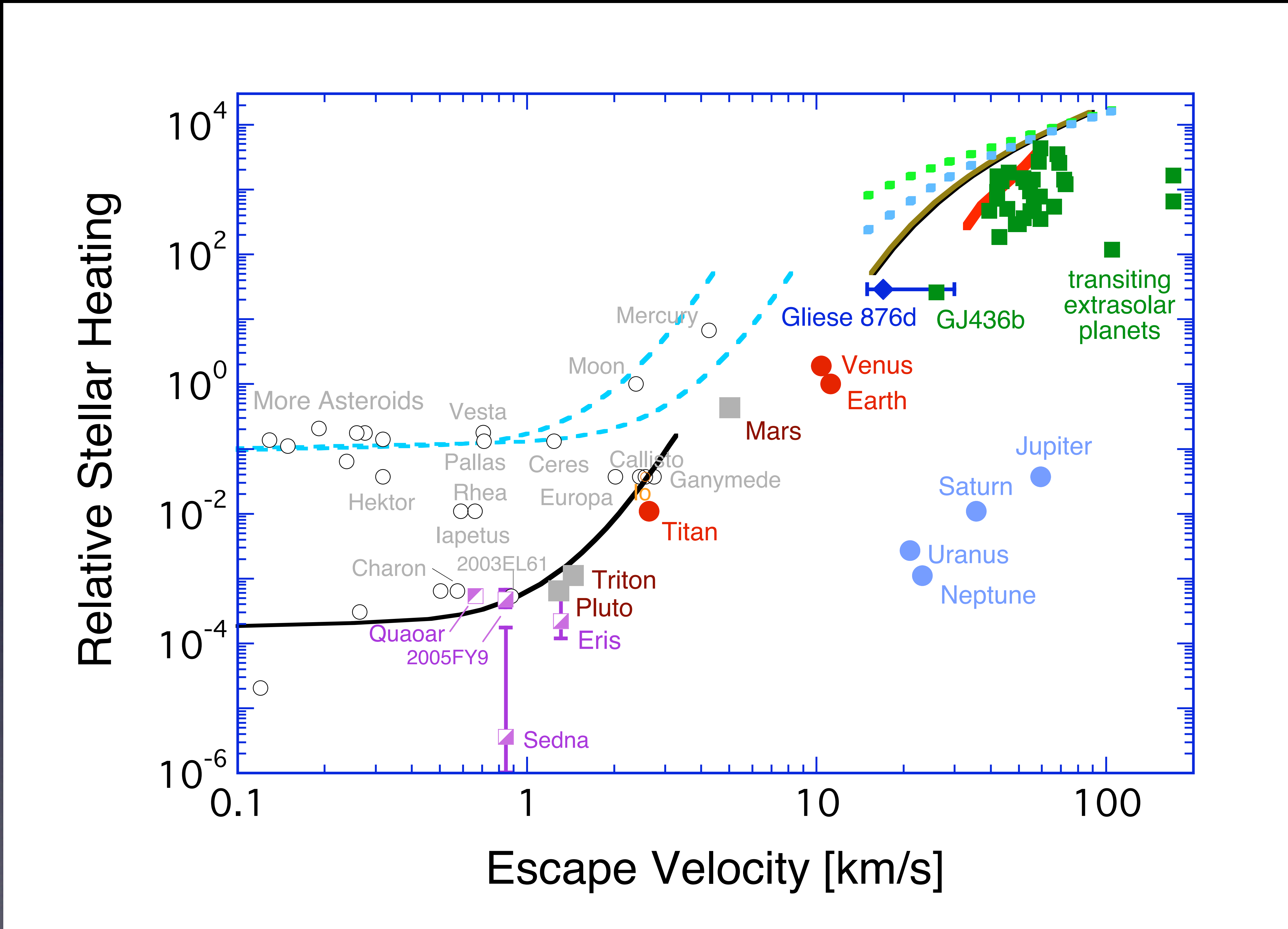
Super Earths & Earths

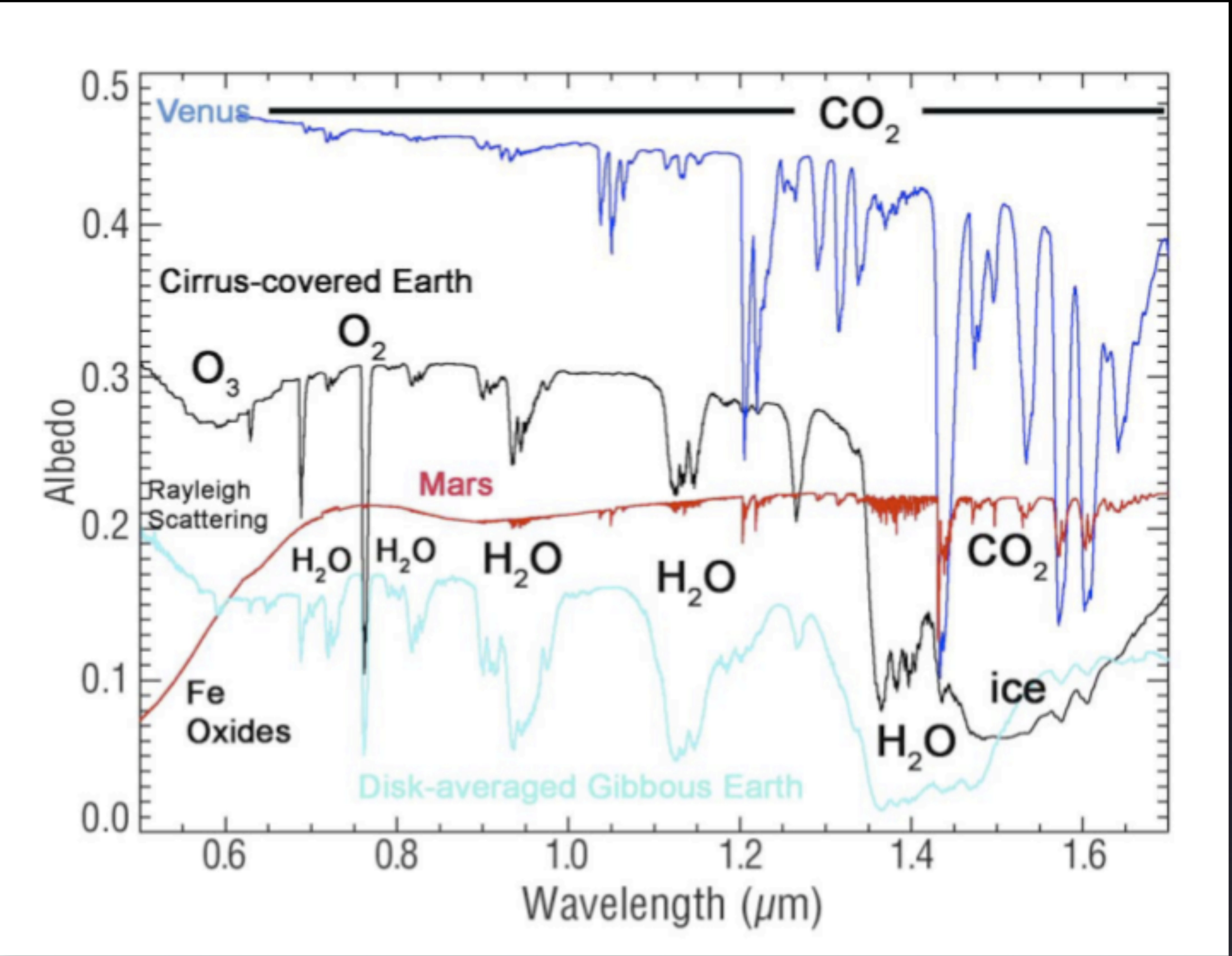
Atmosphere?



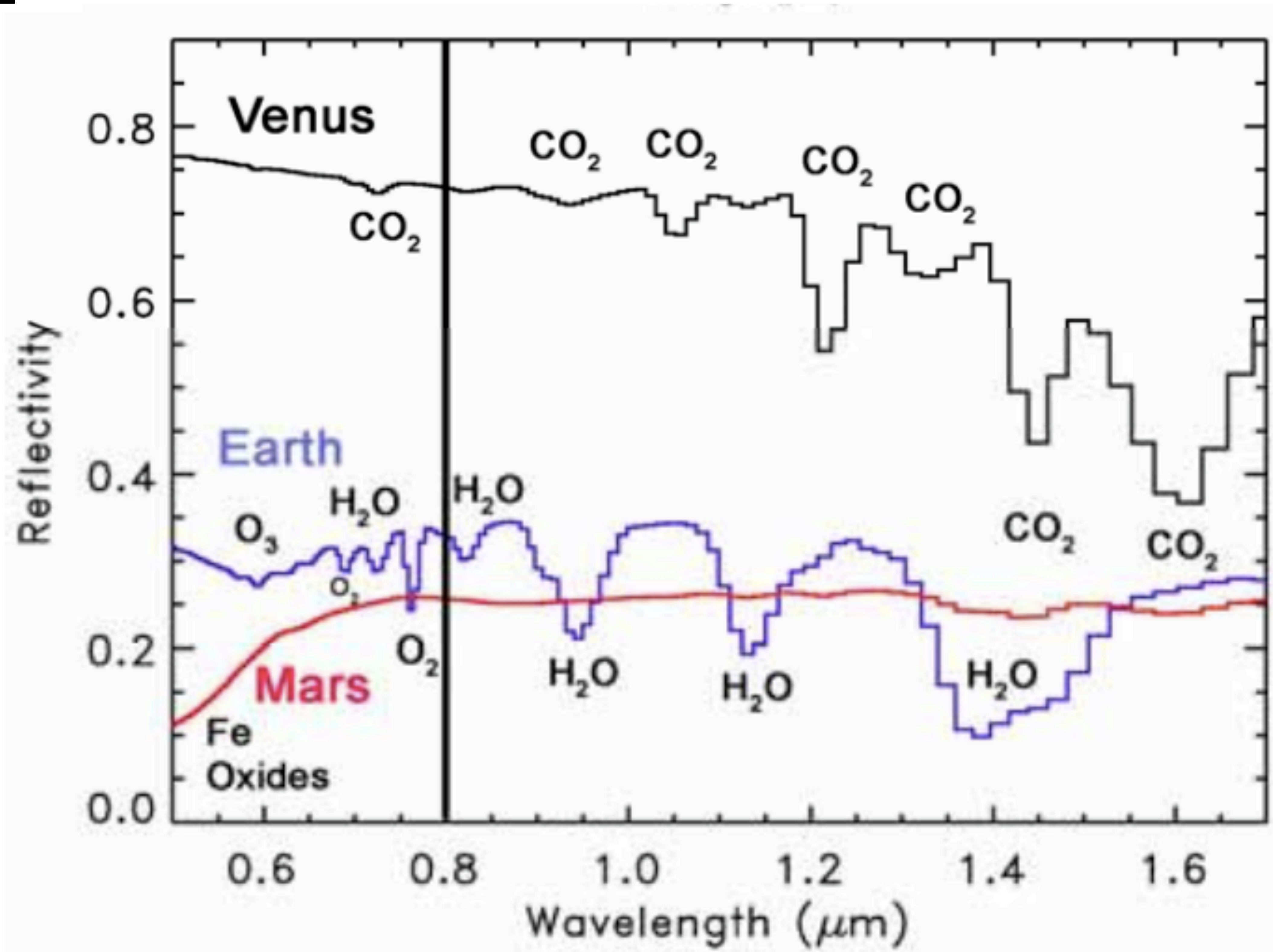
transiting extrasolar planets
Gliese 876d
GJ436b
Mercury
Moon
Venus
Earth
Mars
More Asteroids
Vesta
Pallas
Ceres
Callisto
Ganymede
Europa
Io
Hektor
Rhea
Iapetus
Titan
Chiron
Jupiter
Saturn
Uranus
Neptune
Triton
Pluto
Quaoar
Eris
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.1
1
10
100
Relative Solar Heating
Escape Velocity (km/s)

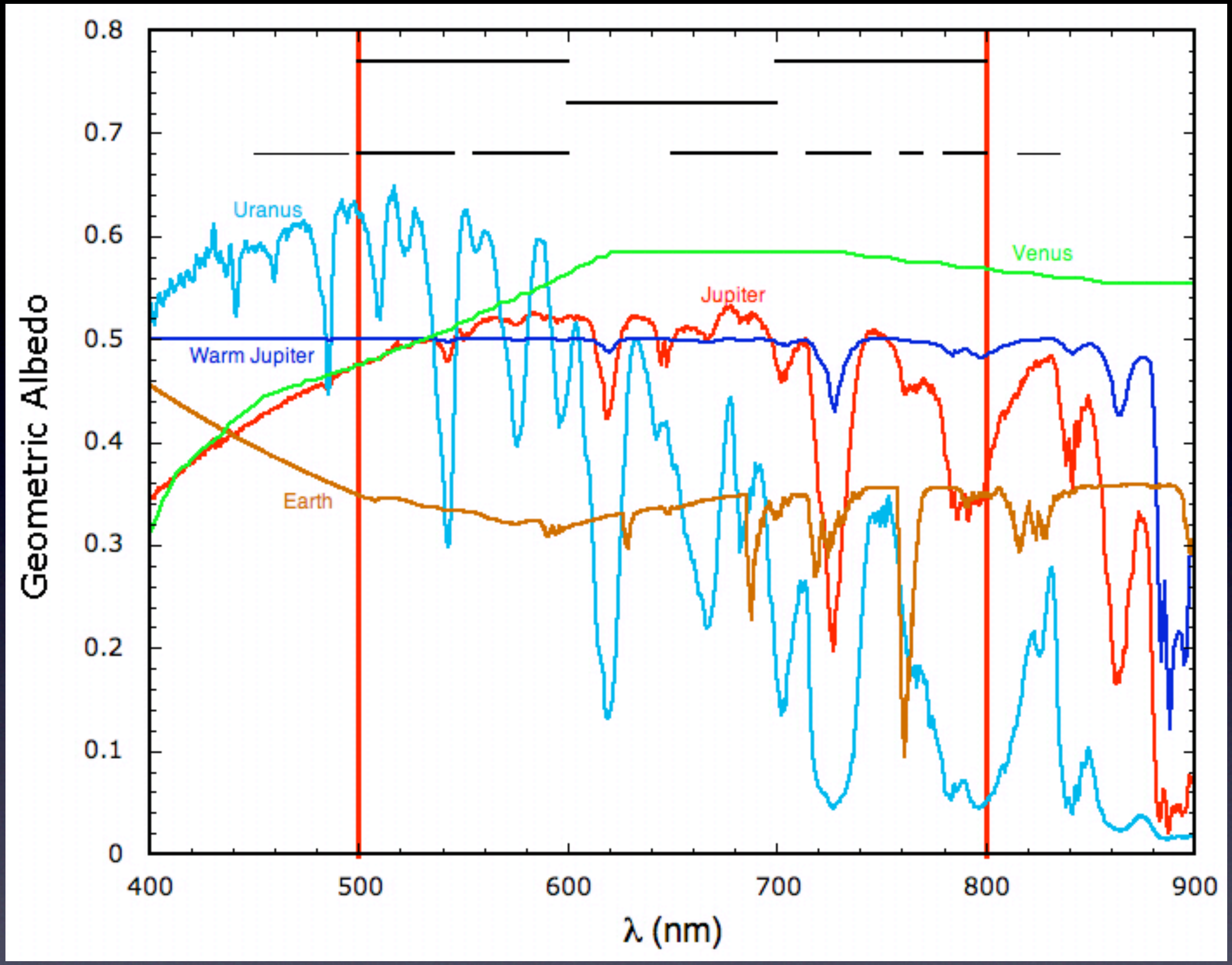
Atmosphere?


Relative Stellar Heating
Escape Velocity [km/s]
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0.1
1
10
100
More Asteroids
Vesta
Pallas
Ceres
Hektor
Rhea
Europa
Iapetus
Callisto
Ganymede
Io
Titan
Mercury
Moon
Mars
Charon
2003EL61
Triton
Pluto
Quaoar
2005FY9
Eris
Sedna
Gliese 876d
GJ436b
transiting
extrasolar
planets
Venus
Earth
Jupiter
Saturn
Uranus
Neptune



0.5
0.4
0.3
0.2
0.1
0.0
Albedo
0.6
0.8
1.0
1.2
1.4
1.6
Wavelength (μm)
Venus
CO_2
Cirrus-covered Earth
O_2
O_3
Rayleigh Scattering
Mars
H_2O
H_2O
H_2O
H_2O
CO_2
Fe Oxides
ice
H_2O
Disk-averaged Gibbous Earth


Venus
Earth
Mars
Reflectivity
Wavelength (μm)
0.8
0.6
0.4
0.2
0.0
0.6
0.8
1.0
1.2
1.4
1.6
CO2
H2O
O3
O2
Fe
Oxides

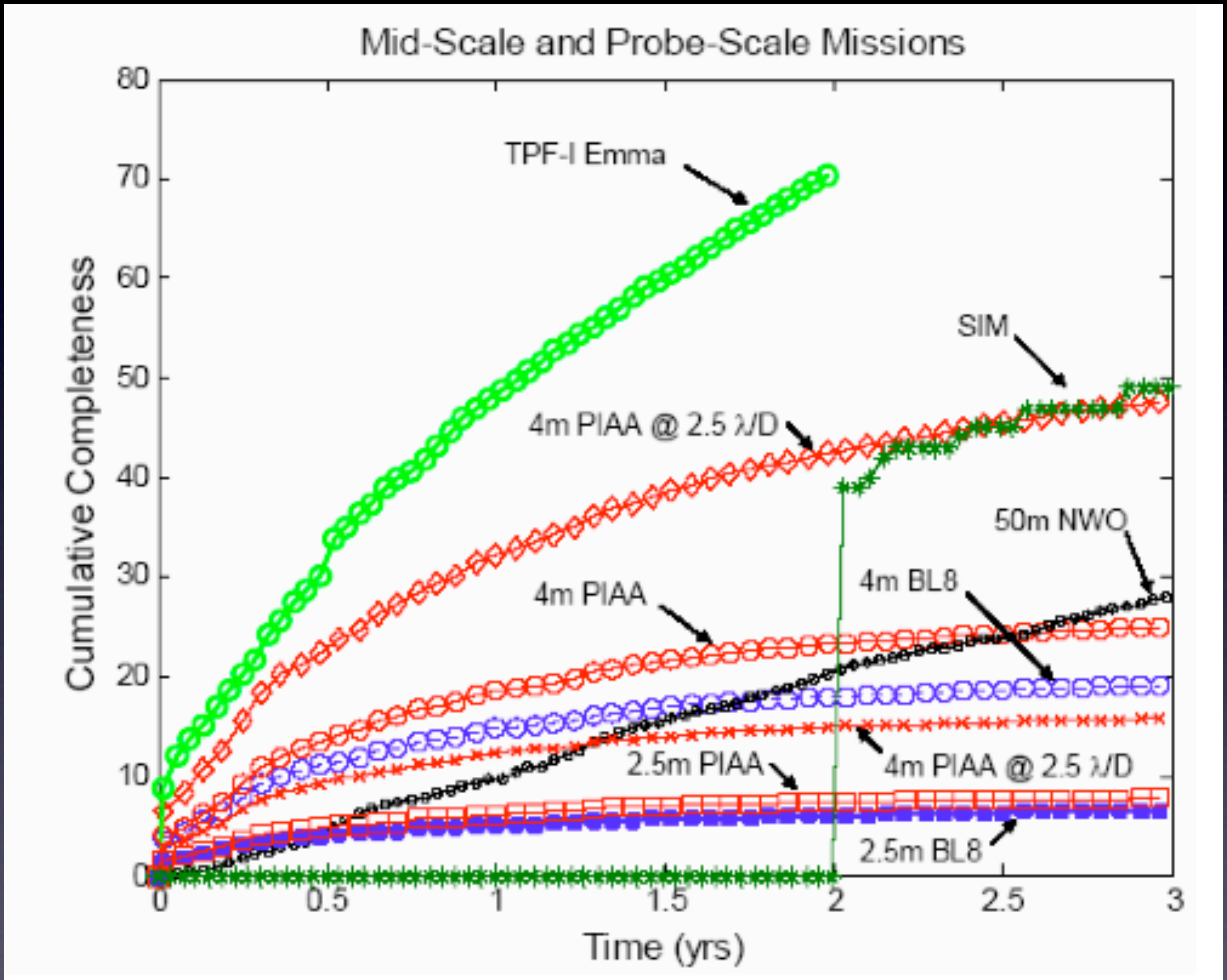


Need to have capability to characterize both typical faint targets and a few excellent ones. Wavelength/ IWA/OWA issues.

Terrestrials

- How constrain mass?
- Spectra challenging for small mission
- Broad band colors likely of limited utility
  - many degenerate interpretations
  - avoid: pale blue dot, no mass, no radius, no spectra

Completeness

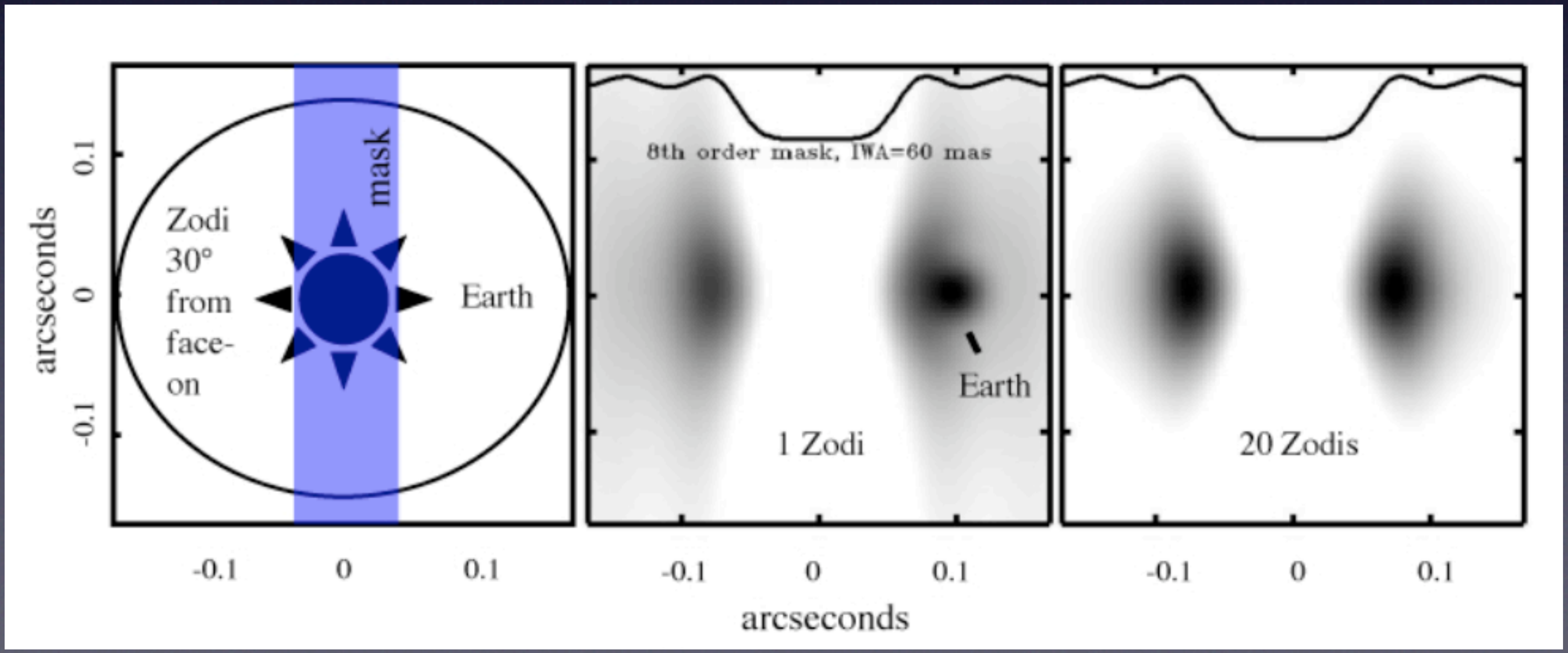


Hunyadi et al 2007

- Small missions find many Earths
- Need to consider "characterization completeness", perhaps ability to detect O_2 or H_2O on an Earth twin or super Earth

Exozodis

- Crucial for direct detection
- Hard to adequately constrain from ground
- Greatest contribution of small mission?



Requirements

Requirements

- IWA/OWA
- Completeness
- Astrometry
- Photometry
  - absolute for albedos & phase coverage
  - relative for colors
- Spectral Resolution & S/N **inside** molecular bands

TPF-C Requirements

(5) *TPF-C* shall be able to detect photons within the spectral range from 0.5 μm to 1.1 μm.
(6) *TPF-C* shall be able to measure the absolute brightness of the Earth twin planet in Requirement (1) in at least one bandpass to within 10%.
(7) For the Earth and Jupiter twins in Requirements (1, 2), *TPF-C* shall be able to measure the relative brightness in at least three broad spectral bands to a relative accuracy of 10% or better.
(8) *TPF-C* shall be able to detect O_2 and H_2O in the atmosphere of the Earth twin planet specified in Requirement (1). Relevant absorption bands and required resolutions are listed in 1.4.1. *TPF-C* shall also be able to detect CH_4 in the atmosphere of a Jupiter twin in this same system. Detection is defined as the ability to measure the equivalent width of a spectral band to within 20% accuracy.
(9) *TPF-C* shall have a minimum spectral resolution of 70 over the entire bandpass specified in requirement (5) to allow the mission to search for absorption bands of unspecified gases or surface minerals.

IWA - OWA

65 ($4\lambda/D$) - 500 mas

TABLE 1. MOLECULAR SPECIES AND SPECTRAL BANDS USED IN THIS STUDY

		σ (cm^{-1})				λ (μm)		
Band	*Species*	*Minimum*	*Maximum*	*Average*	*Resolution*	*Minimum*	*Maximum*	*Average*
1	H_2O	200	300	250	2	33.33	50.00	40.00
2	H_2O	300	400	350	4	25	33.33	28.57
3	H_2O	400	576	488	3	17.36	25	20.49
4	H_2O	1,356	1,500	1,428	10	6.67	7.37	7.00
5	CO_2	587	750	668	4	13.33	17.04	14.96
6	CO_2	930	990	960	16	10.75	10.10	10.42
7	CO_2	1,046	1,102	1,074	19	9.56	9.07	9.31
8	O_3	1,005	1,067	1,036	17	9.37	9.95	9.65
9	CH_4	1,257	1,356	1,306	13	7.37	7.96	7.65
10	CH_4	1,150	1,356	1,253	6	7.37	8.70	7.98
11	Cont.	804	986	895	5	10.14	12.44	11.17
12	Cont.	1,082	1,226	1,154	8	8.16	9.24	8.67
13	H_2O	5,080	5,580	5,330	11	1.79	1.97	1.88
14	H_2O	6,740	7,480	7,110	10	1.34	1.48	1.41
15	H_2O	8,580	9,050	8,815	19	1.10	1.17	1.13
16	H_2O	10,320	10,930	10,625	17	0.91	0.97	0.94
17	H_2O	12,000	12,350	12,175	35	0.81	0.83	0.82
18	H_2O	13,630	14,000	13,815	37	0.71	0.73	0.72
19	CO_2	4,780	5,080	4,930	16	1.97	2.09	2.03
20	CO_2	6,020	6,570	6,295	11	1.52	1.66	1.59
21	CO_2	8,120	8,360	8,240	34	1.20	1.23	1.21
22	CO_2	9,410	9,650	9,530	40	1.04	1.06	1.05
23	O_2	7,840	7,950	7,895	72	1.26	1.28	1.27
24	O_2	13,010	13,200	13,105	69	0.76	0.77	0.76
25	O_2	14,380	14,650	14,515	54	0.68	0.70	0.69
26	O_3	15,250	19,000	17,125	5	0.53	0.66	0.58
27	O_3	30,000	32,000	31,000	16	0.31	0.33	0.32
28	CH_4	4,040	4,570	4,305	8	2.19	2.48	2.32
29	CH_4	5,610	6,190	5,900	10	1.62	1.78	1.69
30	CH_4	9,790	10,280	10,035	20	0.97	1.02	1.00
31	CH_4	11,040	11,390	11,215	32	0.88	0.91	0.89
32	CH_4	12,420	12,850	12,635	29	0.78	0.81	0.79
33	CH_4	13,660	13,900	13,780	57	0.72	0.73	0.73

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21	CO_2	8,120	8,360	8,240	34	1.20	1.23	1.21
22	CO_2	9,410	9,650	9,530	40	1.04	1.06	1.05
23	O_2	7,840	7,950	7,895	72	1.26	1.28	1.27
24	O_2	13,010	13,200	13,105	69	0.76	0.77	0.76
25	O_2	14,380	14,650	14,515	54	0.68	0.70	0.69
26	O_3	15,250	19,000	17,125	5	0.53	0.66	0.58
27	O_3	30,000	32,000	31,000	16	0.31	0.33	0.32
28	CH_4	4,040	4,570	4,305	8	2.19	2.48	2.32
29	CH_4	5,610	6,190	5,900	10	1.62	1.78	1.69
30	CH_4	9,790	10,280	10,035	20	0.97	1.02	1.00
31	CH_4	11,040	11,390	11,215	32	0.88	0.91	0.89
32	CH_4	12,420	12,850	12,635	29	0.78	0.81	0.79
33	CH_4	13,660	13,900	13,780	57	0.72	0.73	0.73

TABLE 1. MOLECULAR SPECIES AND SPECTRAL BANDS USED IN THIS STUDY

		σ (cm^{-1})				λ (μm)		
Band	*Species*	*Minimum*	*Maximum*	*Average*	*Resolution*	*Minimum*	*Maximum*	*Average*
1	H_2O	200	300	250	2	33.33	50.00	40.00
2	H_2O	300	400	350	4	25	33.33	28.57
3	H_2O	400	576	488	3	17.36	25	20.49
4	H_2O	1,356	1,500	1,428	10	6.67	7.37	7.00
5	CO_2	587	750	668	4	13.33	17.04	14.96
6	CO_2	930	990	960	16	10.75	10.10	10.42
7	CO_2	1,046	1,102	1,074	19	9.56	9.07	9.31
8	O_3	1,005	1,067	1,036	17	9.37	9.95	9.65
9	CH_4	1,257	1,356	1,306	13	7.37	7.96	7.65
10	CH_4	1,150	1,356	1,253	6	7.37	8.70	7.98
11	Cont.	804	986	895	5	10.14	12.44	11.17
12	Cont.	1,082	1,226	1,154	8	8.16	9.24	8.67
13	H_2O	5,080	5,580	5,330	11	1.79	1.97	1.88
14	H_2O	6,740	7,480	7,110	10	1.34	1.48	1.41
15	H_2O	8,580	9,050	8,815	19	1.10	1.17	1.13
16	H_2O	10,320	10,930	10,625	17	0.91	0.97	0.94
17	H_2O	12,000	12,350	12,175	35	0.81	0.83	0.82
18	H_2O	13,630	14,000	13,815	37	0.71	0.73	0.72
19	CO_2	4,780	5,080	4,930	16	1.97	2.09	2.03
20	CO_2	6,020	6,570	6,295	11	1.52	1.66	1.59
21	CO_2	8,120	8,360	8,240	34	1.20	1.23	1.21
22	CO_2	9,410	9,650	9,530	40	1.04	1.06	1.05
23	O_2	7,840	7,950	7,895	72	1.26	1.28	1.27
24	O_2	13,010	13,200	13,105	69	0.76	0.77	0.76
25	O_2	14,380	14,650	14,515	54	0.68	0.70	0.69
26	O_3	15,250	19,000	17,125	5	0.53	0.66	0.58
27	O_3	30,000	32,000	31,000	16	0.31	0.33	0.32
28	CH_4	4,040	4,570	4,305	8	2.19	2.48	2.32
29	CH_4	5,610	6,190	5,900	10	1.62	1.78	1.69
30	CH_4	9,790	10,280	10,035	20	0.97	1.02	1.00
31	CH_4	11,040	11,390	11,215	32	0.88	0.91	0.89
32	CH_4	12,420	12,850	12,635	29	0.78	0.81	0.79
33	CH_4	13,660	13,900	13,780	57	0.72	0.73	0.73

Smaller Mission Requirements

	Giants	Terrestrials	Zodis
R	15 - 30	up to 100	~5
detection contrast	10^{-9}	10^{-10}	2×10^{-10}
IWA - OWA	optimize for RV synergy	habitable zone	OWA large
phase coverage	yes	yes	no

Summary

- Detection + Characterization
- Need synergy for mass
- Characterization means spectra or spectrophotometry
  - clouds
  - temperature
  - composition
  - tradeoff

Backup

Completeness for a small coronagraph mission

Planet	Mirror Diameter	Albedo	Planet Size (Earth radii)	HZ Location	Targets	Completeness
Earth	1.5m	0.2	1	1 AU	4	3.5
Earth	1.8m	0.2	1	1 AU	8	7.5
Saturn	1.5m	0.47	9.1	9 AU	213	100.7
Saturn	1.8m	0.47	9.1	9 AU	309	146.8
Jupiter	1.5m	0.44	11	5 AU	306	185.8
Jupiter	1.8m	0.44	11	5 AU	394	264.7
Super-Earth	1.5m	0.2	2	1 AU	5	4.8
Super-Earth	1.8m	0.2	2	1 AU	12	11.1
Super-Earth	1.5m	0.2	2	1.5 AU	22	16.6
Super-Earth	1.8m	0.2	2	1.5 AU	32	26.2
Super-Earth w/ Gas Envelope	1.5m	0.44	4.2	1 AU	8	7.1
Super-Earth w/ Gas Envelope	1.8m	0.44	4.2	1 AU	15	14.8
Super-Earth w/ Gas Envelope	1.5m	0.44	4.2	1.5 AU	35	32.0
Super-Earth w/ Gas Envelope	1.8m	0.44	4.2	1.5 AU	50	46.9

IWA 2.5lambda/D
Dm=25.5
500-600nm

Hunyadi et al 2007

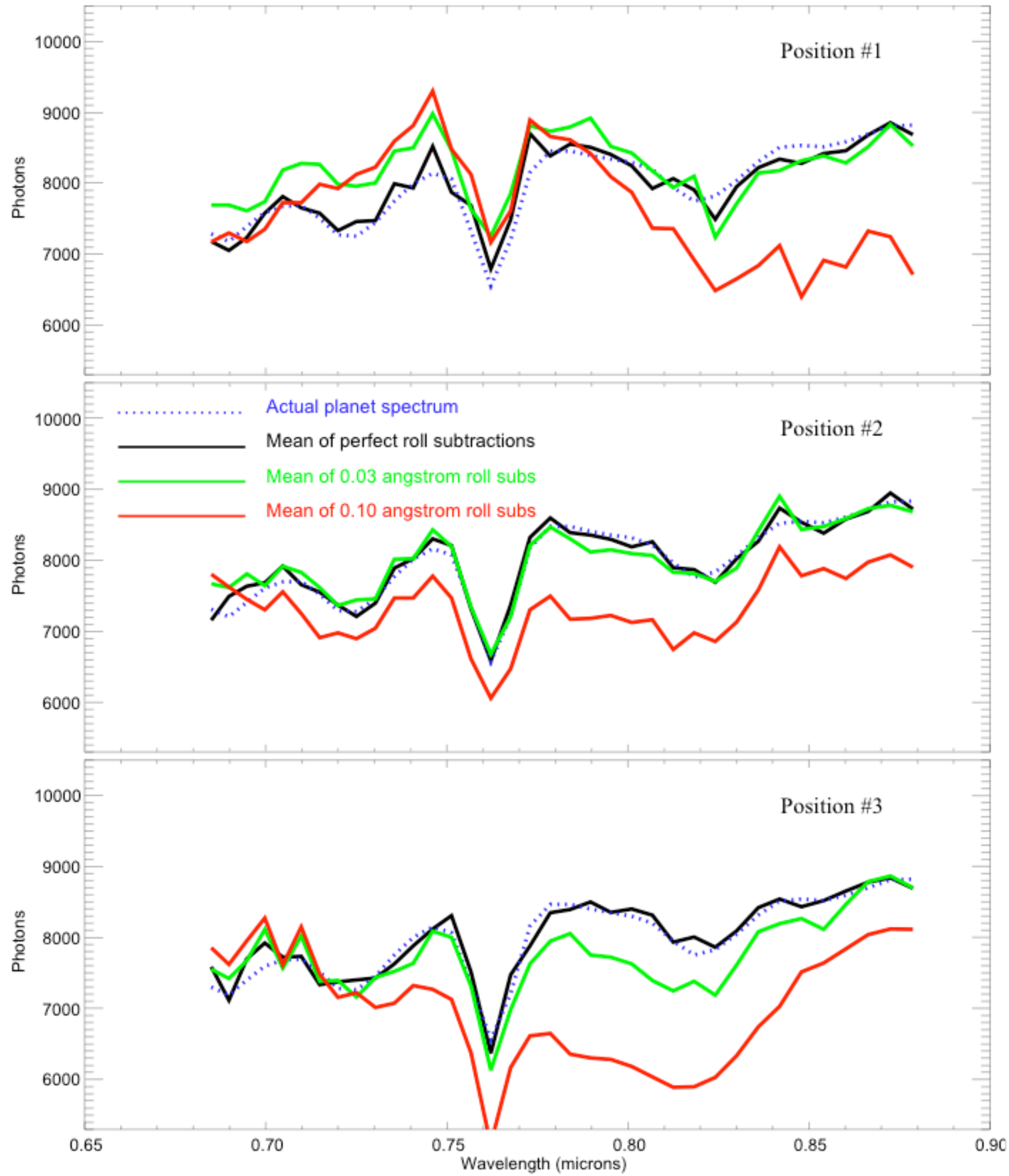
SIM & TPF-C completeness

	Planet Location	Potential Targets	Without SIM Completeness	With SIM Completeness
4m	1 AU	73	54.54	72.16
2.5m	1 AU	19	16.89	18.95
1.5m	1.8AU	7	5.90	6.98

From Sarah:

Attached is the spreadsheet showing the completeness with and without SIM. The without SIM column shows the actual program results from a TPF-C visit scenario from the simulataion. The "with SIM" is the completeness enhancement that SIM would provide TPF-C (i.e. there are some planets in orbits in the associated range that would never be bright enough to see). SIM would, of course, still provide more available mission time for characterization etc.

Rémi: I am not sure how to interpret these numbers. The completeness is already pretty high without SIM and I think this is because she assumes eta=1 here. If eta is not 1 then the completeness without prior information is going to drop by a lot, but the combined coronagraph + SIM should still detect all the SIM planets if the targets are properly selected. I think this reinforces Bob's approach to try to define a good metric to combine indirect (RV or astrometry) and imaging.



Krist et al 2008